# COURSE IN

# EXPERIMENTAL PHYSICS

ALEXANDER

REVISED EDITION

# ELEMENTARY COURSE

IN

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# EXPERIMENTAL PHYSICS

BY

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REVISED EDITION.

BERKELEY, CAL.
1898.

In order to keep the work in Physics at the University of California properly related to that of the secondary schools of the state, it has been found necessary to eliminate many of the more elementary exercises that appeared in the first edition of this course. The remaining exercises have been revised and rearranged and, with some additional matter, will comprise the laboratory course in Elementary Physics to be given in 1898–99.

ARTHUR C. ALEXANDER.

*Berkeley, Cal., July 19, 1898.*

# PREFACE

## TO THE FIRST EDITION.

THIS is not intended to be a complete laboratory manual, or text-book. It simply contains the directions for a series of laboratory exercises in Elementary Physics, representing substantially the first year's work in Experimental Physics at the University of California as given in 1896–97. These directions were originally typewritten and duplicated by means of the mimeograph, a method of preparation that, while allowing the instructor great freedom in modifying and adapting the course to his pupils and the exigencies of the laboratory, also entailed considerable time and labor. As the majority of the exercises will be given during the coming year in their present form, it was deemed best to print the entire course and to modify it, whenever necessary, by supplementary directions. It is not designed to be a course in Physical Measurement, the quantitative feature being retained from necessity and not choice. The primary object of the exercises is to illustrate and impress on the mind of the student the elementary principles of Physics. A course of lectures and recitations with assigned reading and problems is intended to accompany and supplement the work in the laboratory.

In arranging the sequence of exercises an attempt has been made to have those subjects taken up first that are more readily adapted to the laboratory facilities of the secondary schools, and can be easily comprehended by the immature student. In this way, and by giving an annual examination for advanced standing in the subject, it is hoped to induce many of the best equipped preparatory schools to carry their pupils somewhat farther in Physics than is required for admission to the University. The subject of Sound presents peculiar difficulties of presentation to a large class in the laboratory where only one room is available and all are not gifted

alike with the sense of musical pitch. As a result, many interesting and instructive laboratory exercises on this subject had to be omitted, and only two exercises on Sound have been retained in the course.

The author has made a free use of the work of his predecessors, most of these exercises having been adapted from Whiting's "Exercises in Elementary Physics," the text used in the University of California in 1894–95 and 1895–96. The general arrangement and method of presentation is also that of Whiting. This book represents only another step in the development of an elementary laboratory course in Physics. Many of the exercises described have barely passed the tentative stage, and there is still much to be done in the way of addition and elimination. It is the intention to further amplify and modify the course, and the author will be glad of suggestions from any one interested.

As it is impracticable to furnish a complete set of apparatus for each exercise to every student, or pair of students, it has been found best to arrange the apparatus for the separate exercises on consecutive tables and to let the students pass from one table to another as the exercises are completed. A laboratory period of two hours and three-quarters is allowed for the performance of an exercise. A division of the subject matter of each exercise has been made, indicated in the text by an extra space and a dash between the lines. Every student is required to complete the first part in order to be credited with the exercise, and he is required to perform as much of the second part as the laboratory period will permit. The students are also required at the close of each laboratory period to leave duplicate copies of their notes with the instructor for correction.

The author has already mentioned the liberal use he has made of Whiting's "Exercises in Elementary Physics." He desires also to express his great indebtedness to the present members of the Department of Physics for the many ways in which they have helped and encouraged him, and for the hearty interest they have taken in the preparation of these exercises.

ARTHUR C. ALEXANDER.

*Berkeley, Cal., May 1, 1897.*

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## COURSE IN

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### 1. BALANCING COLUMNS.

CAUTION.—Lay aside all gold and silver ornaments while working with mercury.

I. Clamp a U-tube in a vertical position to a burette stand with the bend of the tube resting on the table. Pour into this tube enough mercury to stand about 5 cm. above the table in each arm. Then pour into the longer arm enough water to stand about 13.6 cm. above the end of the mercury column. Work out all air bubbles with a fine wire, and mop up any water resting on the mercury in the short arm with a bit of blotting paper tied to the end of the wire. Measure the heights above the table of the ends of the mercury and water columns, measuring as nearly as possible to the center of the meniscus in each case. Are the liquids in the two branches at the same level? If not, why? What differences are there between the shapes of the free ends of the two columns?

II. Pour into the shorter arm about 5 cm. more mercury, and repeat the measurements of I. Has the length of the column of water been altered by the addition of the mercury, or has it been simply pushed further up the tube?

Find the length of the mercury column that balances the water column in I, and in II. Is it the same in both cases? Find also the ratio of the two balancing columns (water column to mercury column).

III. Fill the longer arm of the U-tube nearly full of water, and measure the length of the water column, and also of the mercury column that balances it. Find again the ratio of the balancing columns. Is it the same as in II? Why should this ratio be equal to the specific gravity of mercury?

IV. Fill one of two beakers, or jars, with water and the other with a saline solution. Place a leg of an inverted Y-tube in each of the liquids. Cautiously draw the liquids up in both legs by suction, and close the stem of the Y air-tight. Why is the liquid higher in either branch than in the corresponding open vessel? Measure the height of each column of liquid above the level of the liquid in the open vessel. Is it the same for both liquids, or not? Why?

Does it make any difference if the branches of the Y-tube are not of the same diameter, or are not held vertically?

Calculate the specific gravity of the saline solution.

V. Fill the two branches of a W-tube, one with water and the other with alcohol. This should be done by pouring the liquids into them alternately, a small quantity at a time. Why is it necessary to observe this precaution in filling?

Make the proper measurements and calculate the specific gravity of the alcohol.

Why is it unnecessary to have the ends of the columns at the same level?

VI. Answer the following questions:—

1. To what class of liquids is the method of the U-tube inapplicable? Why?

2. In the case of highly volatile liquids what advantage has the method of the W-tube over that of the Y-tube?

3. Which of the three is the most general method?

VII. Take a U-tube, labeled "for coal-oil only," fill one branch with water and the other with coal-oil.

Should the water, or the coal-oil, be poured in first; and into which arm, the longer or shorter?

Make the proper measurements and calculate the specific gravity of the coal-oil.

VIII. With the Y-tube and coal-oil instead of the saline solution, find the specific gravity of the coal-oil.

## 2. BAROMETER AND VAPOR PRESSURE.

*Remember the caution of the last exercise.*

I. Take a closed tube, at least 80 cm. long, and wipe it clean and dry with a swab tied to a long and stiff wire. Then fill it with mercury by means of a small funnel. Close the open end with the thumb and invert the tube in a reservoir of mercury. After removing the thumb, does the mercury in the tube fall to the same level as the mercury in the reservoir? If not, why? What is meant by the "barometric pressure"?

Measure the height of the mercury in the tube above that in the reservoir. Is it the same as the height of the barometer given on the blackboard? If it is not, explain why.

II. Observe the following directions in filling the tube and removing air bubbles:—

Fill to within a couple of cm. of the open end. Close with the thumb and invert a number of times, gathering all the air bubbles adhering to the sides into one large bubble. Then hold erect and fill completely, pouring the mercury in slowly, and working out all air bubbles with a fine wire. Again invert in the reservoir. (The amount of air in the tube can be observed by tilting it until the closed end is about 70 cm. above the table.) To further remove the air, place the thumb

tightly over the open end of the tube while in the reservoir, and then raise and carefully invert it a number of times, letting the partial vacuum pass slowly from one end of the tube to the other, and finally, holding it erect with the open end up, take the thumb off, and fill completely, as directed above. This operation should be repeated until the air bubble seen when the tube is tilted has been reduced to the smallest possible size. Note the metallic click when the mercury strikes the top of the tube. (Be careful not to let it strike too hard.) The height of the mercury column ought now to agree, within one cm., with the barometric reading for the day. (See the figures on the board.)

III. Having measured the height of the mercury column above the level of the mercury in the reservoir, draw as much ether as possible into a medicine dropper, and, inserting it into the reservoir under the open end of the tube, introduce a few drops of the ether into the tube, taking great care not to introduce any air. Describe in detail what takes place when the ether is introduced. Does the ether all evaporate, or does it cease to evaporate after a certain amount has been introduced? Explain why, if you can. When is a vapor said to be saturated?

After waiting 15 or 20 minutes for the ether vapor to come to the temperature of the room, measure the height of the mercury column. Why is it less than before the introduction of the ether? What do you find to be the pressure of the ether vapor, in cm. of mercury, at the temperature of the room? (Record this temperature.)

IV (*a*). Pour more mercury into the reservoir, leaving enough space for the mercury in the tube when it flows out. With the tube resting on the bottom of the reservoir, measure again the height of the mercury column, and also the length of the tube occupied by the ether vapor.

(*b*.) Raise the tube so that its lower end is just below the

level of the mercury in the reservoir and repeat the measurements of (*a*).

(*c*.) Answer the following questions:—

1. Was the pressure of the ether vapor in (*a*) the same as in (*b*)?

2. Was its volume the same?

3. The temperature being kept constant, do you find the pressure of saturated ether vapor to depend on its volume, or not?

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V. Remove the ether from the mercury by wiping its surface with a piece of clean blotting paper and then passing it through a pin hole at the point of a paper filter. Clean the barometer tube carefully and repeat the experiment of II and III with benzine instead of ether. What do you find to be the pressure of benzine vapor at the temperature of the room, in cm. of mercury?

## 3. VARIATION OF VAPOR PRESSURE WITH TEMPERATURE.

I. Fill a deep hydrometer jar with water at about 55°. When the water has cooled to 50° (not before), set in the jar a closed U-tube with a few cm. of ether, free of air bubbles, in the closed end, and at least 50 cm. of mercury in the rest of the tube. The mercury before inserting in the water should stand a few cm. lower in the open arm than in the closed, and there should be enough water to completely cover the ether. Describe what takes place when ether is warmed in this way.

Suspend a thermometer in the jar on a level with the ether and read the temperature of the water. At the same time measure the difference in level between the mercury in the two arms of the U-tube. Do this as accurately as you can, by placing a metre rod against the side of the jar and sighting

across the top of each mercury column. It will injure the rod to put it into the water. Using this last measurement and the barometric pressure for the day, find the pressure, in cm. of mercury, of the ether vapor within the closed arm of the tube.

II. If necessary, siphon off a small quantity of the water and replace it with enough cold water to lower the temperature about 3 or 4 degrees. Repeat the measurements of the last section.

In this way make a series of observations of the temperature and pressure of the ether vapor, cooling it down to the temperature of the room or lower.

Do you find the pressure of the ether vapor to vary uniformly with the temperature, or not?

III. Plot the results of I and II on co-ordinate paper and draw a curve to show the relation between the pressure and temperature of ether vapor.*

IV. Take some ether in a small test-tube and immerse it in water at about 30°, adding hot water gradually until the ether begins to boil. Record the temperature of the ether when it first begins to bubble as the boiling point.

Find from the plot obtained in III, the temperature of ether vapor when its pressure is equal to the barometric reading for the day. How does this agree with the boiling point of ether just found? What relation may one infer exists between the temperature at which a liquid boils and that at which the pressure of its vapor becomes equal to the atmospheric pressure? Explain.

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* In plotting the results of an experiment the scales used and the origin of co-ordinates should be chosen, if possible, so that the curve obtained will reach diagonally across the paper. In general the points found should not be connected by straight lines, making a jagged curve, but a "smooth curve" should be drawn to fit these points within the limits of the errors of observation.

V. Take a smaller U-tube, similar to that used in I and II, containing alcohol instead of ether. Place it in a vessel of water, heat the water, and determine the boiling point of the alcohol, using the relation just found.

## 4. DALTON'S LAW.

*Remember the caution of Exercise 1.*

I. Pour some mercury into a 150-gm. bottle with a rubber stopper, to a depth of 2 or 3 cm. If necessary, clean the mercury as in Exercise 2, IV, and be sure that the bottle is clean and dry and free of ether vapor. (If there is any ether vapor in the bottle, it can be removed by inserting a tube and blowing it out.) Insert the short arm of a U-tube, at least 50 cm. long, through the rubber stopper and seal it with wax, using a warm wire to melt the wax around the tube. Tie the stopper securely and invert the bottle, taking care not to entrap any air in the mercury column. Resting the bend in the tube on the table, measure the height of the mercury in the tube above, or below, its level in the bottle. Pour ether into the tube so as to stand in an unbroken column 20 or 30 cm. deep, and attach a rubber bulb to the open end of the tube. By pressing the bulb, force a little of the ether into the bottle, taking care not to force in any air. What is the effect of introducing the ether?

II. Force in more ether until the ether in the bottle is at the same level as the mercury had been before (a trifle above would be better than below this level). The volume of the mixture of air and ether vapor now being the same as the volume of the air before the introduction of the ether, how does the pressure within the bottle compare with the pressure when it contained air alone? Did the evaporation cease immediately after the introduction of the ether, as in Exercise

2, III? If it did not, explain why. (Ask, if you do not know.) What do you find to be the effect of mixing ether vapor with air, the volume being kept constant?

Watch the mercury column and see that its height becomes constant before taking the measurements in III. The mercury ought to become stationary in 20 or 30 minutes.

III. Find by appropriate measurements the increase of pressure within the bottle over the pressure before the introduction of the ether. What does this increase of pressure represent? How does it compare with the pressure of ether vapor when unmixed with air as determined in Exercise 2, III.

Observe and record the temperature of the room. Is it the same as when Exercise 2 was performed? How would the difference in temperature, if there is any, affect the pressure of the ether vapor?

According to *Dalton's law* the pressure of any vapor, or gas, in a gaseous mixture* is the same as it would be if it occupied the space alone. Was the truth of this law confirmed by the results obtained in this exercise and Exercise 2? How?

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IV. Blow the ether vapor out of the bottle with a glass tube and wipe the interior carefully. Remove the ether from the mercury by the method of Exercise 2, V, and repeat I, II, and III with benzine instead of ether.

## 5. BOYLE'S LAW.

Directions for Using the Manometers.—To set one of the mercury columns of the manometer at any particular

* Dalton's law does not apply to a mixture of gases, or vapors, that act on each other chemically, or to a mixture of vapors from liquids that are mutually soluble.

reading, first set the top or bottom of the sliding piece at the required reading and then move the glass gauge up or down in its clamp until the mercury is at the same level.

With the older apparatus with a mirror scale, the glass gauges are raised or lowered, either by themselves or in their sliders, to make any particular setting, and the height of either mercury column is read on the scale when the observer's eye is placed so that the top of the column coincides with its image in the mirror.

I. Set the tops of the mercury columns at the same level, —for instance 0.00 cm. of the scale,—and read the volume of the air in the closed gauge. Under what pressure is this air?

II. Raise the closed gauge until the difference of level between the mercury columns is one-third of the height of the barometer for the day. Read the volume of the air in the closed gauge again. How does the pressure of the inclosed air in I compare with its pressure in II? How does its volume in I compare with its volume in II?

The temperature being constant, do you find the pressure of a gas like the air to vary with its volume, or not? Compare this with the behavior of a saturated vapor. (See Exercise 2, IV.)

III. Lower the closed gauge about 15 cm. at a time, reading at each setting the volume of the inclosed air and the difference of level between the tops of the mercury columns, until they are both at the same level again. Then, in the same way, raise the open gauge, taking similar readings, until the top of the mercury column in the closed tube falls below the graduated portion.

IV. Take the numbers representing the volume and pressure of the inclosed air in II; of what figures were you uncertain when you made your measurements? Of how many significant figures were you certain in each case? Multiply these numbers together and cross out all uncertain figures used in the operation. Of how many significant figures in the result are you certain?

Formulate a general rule for determining the maximum number of significant figures that it is wise to retain when making a calculation from the results of an experiment, and hereafter avoid, as far as possible, the use of unnecessary figures in your calculations.

V. Tabulate the results of I, II, and III, placing the volumes of the inclosed air in one column, the corresponding differences of level between the two columns in another, the pressures as derived from these differences of level in a third, and the products of the pressures into the corresponding volumes in a fourth column. How do these products compare in value?

What is the relation between the pressure and the volume of a gas at constant temperature that you have proved? The correct answer to this question is called *Boyle's law.*

Calling $P$ the pressure, $V$ the corresponding volume, and $K$ a certain constant quantity, write this law in the form of an equation.

VI. Plot your observations on cö-ordinate paper, using the pressures as ordinates and the corresponding volumes as abscissæ. Such a plot is called a "volume-pressure diagram," and the curve obtained in this particular instance is called an "isothermal," *i. e.*, a constant temperature curve. For a perfect gas,—one fulfilling Boyle's law,—it is a segment of an equilateral hyperbola.

## 6. PRESSURE OF GAS AT CONSTANT VOLUME.

I. Set a metre rod in a vertical position alongside the open tube of a simple constant-volume air thermometer with a fixed bulb. Fill the space about and above the bulb with ice-cold water, and stir continuously. Allow a few minutes for the inclosed air to come to the temperature of the bath, and then raise or lower the open tube so as to bring the mercury in the stem of the bulb to the index. Read on the metre rod the

heights of the two mercury columns, and take the temperature of the bath. (The index can be bent to touch either the bulb-stem or the metre rod.)

II. Draw off some of the water and replace it with warmer water so as to raise the temperature of the bath about 10°. After waiting a few moments, repeat the operations and measurements of I.

In this way make a series of observations of the pressure and temperature of the inclosed air, raising the temperature about 10° at a time, and carrying it as high as can be conveniently done with boiling water. How did the pressure of the inclosed gas (air) alter as its temperature increased? Was the rate of change uniform?

III. Calculate from your results, using the atmospheric pressure for the day, the pressure that the gas would have at 0°, if its volume was kept constant? Find the ratio of the average increase in pressure per degree to the pressure at 0°.

Calling $P_0$ the pressure at 0°, $P_t$ the pressure at $t$°, and $a$ the ratio just found, write the equation connecting the pressure and temperature of a gas when the volume is constant.

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IV. Plot the results of II, plotting the temperatures as abscissæ and the pressures as ordinates.

Draw the straight line that agrees most nearly with the points located on the plot. Find the rise of this line (*i. e.*, the increase in pressure of the gas) for a change of 100° in temperature, and also, from the plot, the pressure of the gas at 0°. From these calculate the ratio of the increase in pressure per degree to the pressure at 0°. How does this agree with the result found in III? Why should this last be the more reliable of the two results?

V. What would be the pressure of a gas at —273° C.? If the pressure of a gas depends on the motion of its molecules, would the molecules have any motion at —273° C.? Then,

as heat is the energy due to molecular motion, could a body be cooled below —273° C.?

This temperature is called *absolute zero*. The temperature measured in Centigrade degrees from absolute zero is called the *absolute temperature*.

## 7. EXPANSION OF GAS UNDER CONSTANT PRESSURE.

NOTE.—The air thermometer used in this exercise is constructed so that when the top of the sliding piece is at the zero of the scale, the bottom of the clamp for holding the open tube is approximately at the same level as the lower end of the stuffing box for the closed tube. The scale as read at the top of the slider will therefore give the difference of level between the lower end of the open-tube clamp and that of the stuffing box.

I. Fill the space about the closed tube, or bulb, of the air thermometer with ice-cold water. Set the slider at the zero of the scale, and adjust the mercury columns, somewhat as was done in Exercise 5, so that the mercury in both tubes is at the level of the lower end of the stuffing box. (The mercury column can be set quite accurately by sighting across the end of the brass tube surrounding the glass.) Read the volume of the inclosed gas (air) and take the temperature of the water bath.

II. Raise the temperature of the bath as in Exercise 6, II, about 10° at a time, and repeat for each temperature the operations and measurements of I. What was the pressure of the inclosed air in each case? Was it the same? Was the expansion of the air uniform?

III. Calculate the average expansion for a rise of one degree in temperature. If no observation was made at 0°, cal-

culate from your results the volume that the gas would have had at 0°. Find the ratio of the average expansion per degree to the volume at 0°,—in other words, the *cubical coefficient of expansion* between 0° and 1°. How does this quantity compare with the ratio of the increase in pressure per degree to the pressure at 0° when the volume is kept constant? (See Exercise 6, III.)

Calling $V_0$ the volume of a gas at temperature 0°, $V_t$ the volume at $t$°, and $a$ the coefficient just found, write the law of expansion of a gas at constant pressure in the form of an equation. This is called the *law of Charles* or *Gay-Lussac.*

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IV. Plot the results of I and II on co-ordinate paper, plotting the temperatures as abscissæ and the volumes as ordinates.

Find from this plot, by the method used in Exercise 6, IV, the expansion for a change in temperature of 100° and the volume of the gas at 0°. Calculate from these the coefficient of expansion between 0° and 1°. Is the result the same as that obtained in III?

V. Take a series of measurements for descending temperatures, as was done for ascending temperatures in II.

VI. Plot the results of V and find the contraction of each c. c. of the gas, at constant pressure, between 0° and 1°, by the method of IV. Does the result agree with that obtained for the expansion of the gas?

## 8. LINEAR EXPANSION.

I. Measure the length of a metal rod about one metre long, noting the kind of metal. Place it in the trough of a linear expansion apparatus and fill the trough with water from the faucet. Take the temperature of the water and read the position of the free end of the rod. (If the apparatus

with a micrometer screw is used, ask for additional directions.)

II. Siphon off some of the cold water and replace it with warm water from the heater at the sink so as to raise the temperature about 10°, and read again the position of the end of the rod. In this way take a series of readings of the temperature and the corresponding positions of the free end of the rod, using Bunsen burners to raise the temperature of the water from 40° to 90°. Do you find the expansion of the rod to be uniform?

III. What was the total expansion of the rod in centimetres? (If the lever and scale arrangement was used, the expansion as read on the scale will have to be multiplied by a constant factor to obtain the actual expansion of the rod. Study the construction of the apparatus and make the proper measurements in order to find this reduction factor.) What was the average expansion for one degree rise in temperature? What was the average expansion of each centimetre of the rod (in cm.) for one degree rise in temperature? This is called the *linear coefficient of expansion* of the metal.

IV. Plot the results of I and II on co-ordinate paper, plotting the temperatures as abscissæ and the expansion readings as ordinates.

Draw the straight line that agrees most nearly with the points found on the plot and find the rise of this line (increase in length of rod) for a change of 80 to 100 degrees in temperature. Calculate from this the linear coefficient of expansion of the rod. Why should the result thus obtained be more accurate than that obtained in III.

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V. After the water has reached a temperature of about 90°, siphon off some of the warm water, if necessary, and replace it with enough cold water to lower the temperature about 10°. In this way cool the rod down, 10° at a time, taking another series of observations of the temperature and

the position of the free end of the rod. Lower the temperature as much below that of the room as you can by the use of ice. Do you find the contraction of the rod to be uniform?

VI. Plot the results of I, II, and V on co-ordinate paper and draw the curves for ascending temperatures and for descending temperatures. Do these two curves coincide? If not, give a reason for the difference.

VII. Find, if time permits, the coefficients of expansion of some other metals. (Two or three observations will be sufficient provided the change in temperature is not too small.)

## 9. EXPANSION OF LIQUIDS.

I. Counterbalance a bottle with a solid glass stopper. Fill it with coal-oil, and, before inserting the stopper, place it up to its neck in water fresh from the faucet. When the coal-oil has come to the temperature of the water, insert the stopper. Wipe the outside of the bottle and find, by replacing it on the balance and weighing, the mass of the coal-oil necessary to completely fill the bottle at this temperature. Record the temperature.

II. Raise the temperature of the bath about 10° by replacing some of the cold water with warmer water, and set the bottle again in the water. With a cloth mop up the coal-oil that is forced out of the bottle until no more is forced out. Then take the temperature of the water and find the mass of the coal-oil now in the bottle. If it has decreased, explain why.

III. Raise the temperature of the bath about 10° at a time, repeating for each 10° rise in temperature the measurements, etc., of II, using finally boiling water from a kettle.

IV. Cool the bottle down carefully, and find its cubical contents by filling it with water and weighing, using 0.998

gm. per c. c. as the density of water at the temperature of the room.

Calculate for each temperature in I, II, and III, the volume of one gramme of coal-oil.

V. Plot your results on co-ordinate paper, plotting the temperatures as abscissæ and the volumes as ordinates. Was the expansion of the coal-oil uniform, according to your results?

Draw the straight line that agrees most nearly with the points found on your curve. Measure the rise of this line, in c. c. of the scale, for as great a difference in temperature as can be obtained from your plot. Having found in this way the average expansion of a certain volume of coal-oil for a certain rise in temperature, calculate the volume at 0° and the average expansion of each c. c. at 0° for one degree rise in temperature. The result will be the *volumetric* or *cubical coefficient of expansion* of coal-oil at 0°.

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VI. Repeat I–V, as far as time permits, with alcohol instead of coal-oil.

## 10. LATENT HEAT OF FUSION.

I. Put about 100 gm. of crushed ice into a pint cup and take its temperature. Heat it over a low flame, stirring continuously, and take the temperature from time to time until the ice is all melted. Did the temperature change any while the ice was melting? If it did not, what became of the heat imparted by the flame?

II. Weigh a metal cup, holding about a quart, and have ready in another vessel at least 500 gm. of water at about 45°. Place a piece of ice (about 100 gm.) on some absorbent cotton on the balance and counterbalance the ice and

cotton with shot. Preserve the counterpoise. Take the exact temperature of the warm water. Place the ice in the cup, handling and wiping it with the cotton, which should be replaced on the balance. Without loss of time, pour most of the water over the ice. Stir the mixture thoroughly and take the temperature when the ice disappears. The final temperature of the mixture should be the same as that of the room. If it is below, add more of the warm water; if above, the experiment should be repeated, using either more ice or less water.

Having previously weighed the cup, the mass of the mixture can be found by weighing and subtracting the mass of the cup; and the mass of the water used can be found by subtracting from this the mass of the ice. This latter quantity can be found by replacing the counterpoise and wet cotton on the balance and finding the weight to be added to restore equilibrium.

If the final temperature of the mixture is the same as that of the metal cup at first (viz., that of the room), the heat gained, or lost, by conduction will be negligible. Explain why.

III. Calculate in order the following quantities, using as the unit of heat the amount of heat required to raise one gramme of water one degree in temperature*:—

1. The heat lost by the water poured over the ice.

2. The heat required to raise the water from the melted ice from 0° to the temperature of the mixture.

3. The total heat absorbed by the ice in melting.

4. The heat absorbed by each gramme in melting.

The latter quantity is called the *latent heat of fusion* of water.

* This unit of heat is known by the names *calorie*, *therm*, and *gramme-degree*. Another unit of heat frequently used is the *Calorie*, or kilogramme-degree.

IV. Repeat I–III with great care, as many times as possible, and compare the values obtained for the latent heat of fusion water.

## 11. LATENT HEAT OF VAPORIZATION.

I. Fill a small copper boiler about two-thirds full of water and insert through the cork stopper a safety-tube with an opening about 2 cm. from its lower end. Connect to the boiler a rubber tube with a trap for collecting the water condensed in the tube and a delivery-tube 4 or 5 cm. long. Bring the water in the boiler to a boil. (If at any time steam issues vigorously from the safety-tube, it means that the water is low and the boiler needs refilling.)

Weigh out 500 gm. of ice-water in a beaker. Counterbalance it with shot and take its temperature. Empty the water out of the trap and hold it so that the delivery-tube is well immersed in the ice-water. Stir and observe the temperature as it rises. When the temperature reaches a point as much above the temperature of the room as the original temperature of the ice-water was below, remove the delivery-tube. Stir and take the temperature again carefully. Replace the beaker on the balance and find the increase in the mass of the water due to the steam that has been condensed.

II. If the temperature of the water was as much above the temperature of the room after the condensation of the steam as it was below before the introduction of the steam, we may safely neglect the effect of the surrounding air, for the beaker will lose to the air as much heat in the latter part of the experiment as it gains from the air in the first part. Neglecting also the thermal capacity of the beaker and using the same unit of heat as in Exercise 10, calculate in order the following quantities:—

1. The total amount of heat imparted to the water in the beaker.

2. The heat given out by the water from the condensed steam in cooling from 100° to the temperature of the mixture.

3. The total amount of heat given out by the steam or water vapor in changing from the state of a vapor to that of a liquid.

4. The heat given out by each gramme of water vapor in changing from the gaseous to the liquid state.

The latter quantity is called the *latent heat of vaporization* of water.

III. Repeat I and calculate again the latent heat of vaporization of water. Repeat until concordant results are obtained. Do not reject any of the results unless there is good reason for doing so.

## 12. SPECIFIC HEAT.—METHOD OF FUSION.

I. Weigh three, or more, balls of different metals.

II. Suspend one of the balls in a vessel of boiling water for a few moments. Melt with it a cavity in a block of ice deep enough to hold the ball, and replace it in the boiling water. Let it remain long enough to acquire the temperature of the water. Carefully dry the cavity in the ice with some absorbent cotton. After squeezing the water out and weighing the cotton, transfer the ball quickly to the cavity and cover it closely with the weighed cotton to exclude the air. When the ball has come to the temperature of the ice, soak up with the cotton the water from the melting ice, taking care not to wipe the exterior surface of the ice. Replace the absorbent cotton on the scales and find the mass of the water from the melted ice.

III. Repeat II with each of the other balls.

Calculate the heat given out by each ball in cooling from

the temperature of boiling water to that of the melting ice, using 80 for the value of the latent heat of fusion of water. How many units of heat were given out by each ball in cooling one degree? How many units of heat were given out by each gramme in cooling one degree? Was this quantity the same for each ball?

IV. DEFINITIONS.—The *thermal capacity* of a body is measured by the amount of heat required to raise its temperature one degree. The *specific heat* of a substance is the ratio of the heat required to raise a unit mass one degree in temperature to the heat required to raise an equal mass of water one degree in temperature. Hence, if the latter is taken as the unit of heat, the specific heat of the substance will be directly equal to the number of units of heat required to raise one gramme one degree in temperature.

Of the results found in III, which represent the thermal capacities of the balls, and which the specific heats?

Are the results of this exercise very reliable? What do you consider the chief sources of error?

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V. Repeat I–IV with other balls, of the same or different metals, and find the specific heat of as many metals as you have time for.

## 13. SPECIFIC HEAT.—METHOD OF MIXTURE.

I. Weigh out 300 gm. of lead shot and heat it in a double boiler. After the water in the boiler comes to a boil, stir the shot thoroughly with a wooden paddle and take its temperature. Repeat this until the temperature of the shot becomes constant. Have about 75 gm. of ice-water ready. Take successively the temperature of the shot and of the water, stirring each, and pour both into a metal cup. (This should

be done quickly so as not to let the shot and water change any in temperature before being mixed.) Stir the mixture and take its temperature until the latter becomes fairly constant. Record the final temperature of the mixture.

From the results obtained calculate:—

1. The number of units of heat gained by the water.

2. The number of units of heat lost by the shot (in terms of *s*, the specific heat of lead).

Form an equation between these two quantities, assuming that the heat lost to the jar and room can be neglected, and calculate *s*, the specific heat of lead.

II. Estimate, as nearly as you can, the mass of water which would have brought the mixture to the temperature of the room.

Repeat I, using this mass of water and the same mass of lead shot (300 gm.), both being at the same temperature as in I., Why should the value of the specific heat thus found be more reliable than that found in I?

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III. Find in a similar manner the specific heats of copper and brass, using at first about 100 gm. of each to 75 gm. of ice-water.

IV. Find also the specific heat of coal-oil, using instead of the metal cup a bottle with a cork into which the warm coal-oil and the ice-water can be poured and shaken together, and taking about 1 gm. of coal-oil at 70° to 2.5 gm. of water at 10°. Care should be taken in warming the coal-oil not to ignite it.

## 14. MECHANICAL EQUIVALENT OF HEAT.

I. Take two bottles, and put in each of them a kilogramme of lead shot. Place these bottles in an ice-chest to cool.

(The bottles should be corked to keep the shot dry and set in a box to prevent them from being broken.)

When the shot in one of the bottles has cooled about 3° below the temperature of the room, shake it thoroughly and take its temperature carefully. Then pour it into a tube of pasteboard, or bamboo, about one metre long and close the end of the tube securely. Raise the end of the tube containing the shot with sufficient velocity to keep the shot from falling, and when it reaches a vertical position, let the shot fall vertically, like a solid mass, through the length of the tube. Repeat this again and again, keeping count of the number of times the shot falls.

PRECAUTIONS, ETC.—The shot should not be raised too suddenly, so as to throw it violently against the side of the tube, nor should the tube be raised or lowered so as to lengthen or shorten the distance fallen through by the shot. It is well also to hold the tube about a foot from each end, so that there is no danger of any heat being imparted to the shot from the hands. The following method of raising the shot and reversing the tube is recommended: Lay the tube on the table, and raise the end containing the shot, while the other end rests on the table. Let the shot fall, and then lower the raised end. Raise the other end, which now contains the shot, and let the shot fall again. Then lower this end, and again raise the end which contains the shot; and so on.

After the shot has fallen through the length of the tube a hundred times, insert a thermometer through a side opening, and take its temperature again. Why has the temperature of the shot risen above that of the room?

II. Replace the shot in the ice-chest to cool, and while the tube is still warm, repeat the operations and measurements of I, using the shot from the other bottle, which should be about 3° below the temperature of the room. (Its tempera-

ture can be raised by shaking the bottle, if it is too low.) Repeat the experiment in this way, cooling one bottle of shot while using the other, until concordant results are obtained.

III. Remove the stopper and measure the distance from the end of the tube to the top of the shot. What is the average distance fallen through by the shot in each reversal of the tube? In one hundred reversals? How far would the shot have to fall to raise its temperature one degree? How far would one gramme have to fall to raise its temperature the same amount (one degree)? How much work, in gramme-centimetres, would be required to raise one gramme of shot one degree in temperature? The specific heat of lead is about 0.032. Using this, calculate, in gramme-centimetres, the amount of work necessary to raise one gramme of water one degree in temperature. This last quantity is called the *mechanical equivalent* of the heat unit.

## 15. RADIATION.

I (*a*). Place your hand a few cm. below a Bunsen flame. Does it feel warm? Can heat be conveyed to it by conduction or by convection (air-currents) from the flame? If not, how was the heat conveyed to your hand?

(*b*.) Clamp a sheet of tarnished metal to a burette stand in a horizontal position, and place the flame underneath it. Replace your hand below the flame. What effect has the sheet of metal on the heat felt by your hand? Is it greater or less than in (*a*)?

II. Take two metal vessels of the same size, one with its exterior surface polished, and the other with its exterior surface blackened. Fill both vessels to the same depth with boiling hot water. Stir and take the temperature of the water every minute as it cools, for 10 or 15 minutes. Was

the cooling effect due to conduction and convection approximately the same for both vessels? Did you find that due to radiation to be the same?

III. Fill the two vessels used in II with cold water from the faucet, and place them about 20 cm. from a Bunsen flame. Take the temperature of the water in each every five minutes, for a quarter of an hour or longer. In which vessel did the temperature of the water rise the more rapidly? Do you find the better radiator to be the better or worse absorber of radiant energy? Explain why this relation must be true in order that bodies exposed alike to radiation shall remain in thermal equilibrium.

IV. Take two blackened metal vessels of the same size, and place one within a cylinder with polished interior, and the other within a similar cylinder with its interior blackened. Fill both vessels with hot water, as in II, and observe their rates of cooling. In which vessel did the water cool the more rapidly? Why?

V. Repeat III with a sheet of metal (or asbestos) placed in the flame at an angle of about 45° with the vertical. Which do you find to be the better radiator, the flame or the hot metal sheet?

VI. Extinguish the burner, and set the two blackened vessels used in IV at 25 and 50 cm. respectively from the hottest part of the metal (or asbestos) sheet, so that they are not exposed to radiation from any other source (as a sunny window or another burner on the table). The surface of the vessels not exposed to the flame should be protected from loss of heat by some non-conductor (as a cardboard or paper shield). Fill the three vessels with cold water from the faucet and light the burner. Be sure that the surface of the vessels is dry. At the end of five minutes record the temperature of the water in the nearer vessel. Note carefully and record the time it takes the water in the other vessel to reach the same

temperature. Why should the water in the farther vessel heat more slowly than in the nearer? How did the heat absorbed by the nearer vessel compare with that absorbed by the farther in the same time? Assuming that the amount of radiant energy received by a given surface varies as some integral power of its distance from the source of radiation, what do you find the power in question to be? Is it direct, or inverse?

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VII. Fill one of the blackened vessels with boiling-hot water and the other with water at about 50°, and note, as they cool down, the temperature of the water at intervals of one minute each. Is the rate of cooling uniform and the same for both vessels, or not? How does the rate of cooling vary with the difference between the temperature of the vessel and that of the surrounding air?

The correct answer to the last question would give what is called *Newton's Law of Cooling*.

## 16. MEASUREMENT OF SURFACE TENSION.

General Directions.—Whenever the beaker used in this exercise is emptied, wipe it carefully and rinse it thoroughly with warm water before filling it again with another liquid. The rectangles used should also be cleaned at the same time.

In reading the balance the eye should be placed so that the pointer, or part of it, appears to coincide with its image in the mirror.

I. Fill a beaker, about 7 cm. in diameter, with a solution of soap in water. Replace the pans of a Jolly balance by a wire rectangle 2 cm. wide, hung vertically, and hold the beaker so that the upper side of the rectangle is just level with the surface of the soap solution. Read the balance.

Lower the beaker slowly and steadily. Does the upper part of the rectangle cut through and leave the surface without stretching the spring? If not, why? Lower the beaker until a film forms within the upper part of the rectangle, and again read the balance. To what force is the elongation of the spring due? How does the elongation vary with the force producing it?

Repeat the measurements until concordant results are obtained.

II. Repeat the measurements of I, using rectangles about 4 and 6 cm. wide. How do you find the tension of the film to vary with its width?

III. Find the elongation of the spring produced by a one-gramme weight.

Calculate the tension in dynes (980 dynes = weight of one gramme) of each of the three films in I and II. As a film has two surfaces, the width of the surface in apparent tension, neglecting that about the wires, will be equal to twice the width of the rectangle. Using this, calculate in dynes the average tension of the soap solution across each cm. of the surface.

The tension across a unit length of the surface of a liquid is called the *surface tension* of that liquid.

IV. Clean the beaker and rectangle thoroughly, and repeat the measurements of II with water fresh from the faucet. (If a film cannot be formed, take the reading of the balance when the upper part of the rectangle breaks away from the surface.) Repeat until concordant results are obtained.

Calculate the surface tension of the water. How does it agree with that of the soap solution? Which has the greater surface tension, according to your measurements? Which appears to have the greater surface tenacity? What is the difference between *surface tension* and *surface viscosity*, or *tenacity?*

V. With the 4-cm. rectangle find the surface tension of alcohol.

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VI. Using the same rectangle, find the surface tension of hot water from the heater at the sink, and also of water cooled with ice. Be sure the ice is clean. Does the temperature affect the surface tension appreciably and how?

## 17. PRINCIPLE OF MOMENTS.

I (*a*). Take a circular disc free to rotate about a pivot through its center. Fasten two spring balances to two screw-eyes in the disc at equal distances on opposite sides of the center, and to two similar screw-eyes in the table, so that the balances are parallel. Tighten both cords, and read the balances.

Pull one of the balances out so as to double the tension, and adjust the cords so that the balances are still parallel. What does the other balance register? When a force tends to produce rotation about a point, what is the effect of doubling this force upon the force opposing the rotation?

(*b*.) Move one of the balances to a screw-eye at twice the distance from the center as in (*a*) and pull it (parallel to the other balance) so that it registers the same tension as before. Read both balances.

The perpendicular distance from the center of rotation upon the line of action of a force is called its *lever arm*. When a force tends to produce rotation about a point, what do you find to be the effect of doubling the lever arm upon the force opposing the rotation?

(*c*.) The tendency of a force to produce rotation about a point, according to (*a*) and (*b*), is proportional to the product of what two quantities? This product is called the *moment* of the force about the point considered, and is usually taken

positive in sign when the force tends to produce rotation in a counter-clockwise direction, and negative when it tends to produce rotation in the opposite direction.

II (*a*). Take a beam suspended so as not to rub the surface of the table, and connect its middle point to a screw-eye in the table by means of a spring balance. Attach two balances to two screw-eyes, one metre apart, on the opposite side of the beam at unequal distances from its middle point and to corresponding screw-eyes in the table. Tighten the cord attached to the first balance. Read all three balances, and measure the distances between their points of attachment to the beam.

(*b*.) Loosen, or tighten, the cords a little and read the balances again.

(*c*.) Shift the two balances to two other screw-eyes on the beam, one metre apart, and repeat (*a*).

(*d*.) How do the directions of the forces measured by the two balances compare in each case with that measured by the single balance? In what directions do the forces measured by the two balances tend to rotate the beam? Calculate the moment of each of the forces in (*a*) about some point of the beam. Give these moments their proper signs, and find their algebraic sum. Do the same for the forces in (*b*) and in (*c*). What is your conclusion as to the value of the sum of their moments when a number of parallel forces in the same plane act on a rigid body so that it is held in equilibrium?

III. Attach three balances at random to the disc used in I, and to screw-eyes in the table. Tighten the cords connected to them and read the balances. Extend the line of action of each force, if necessary, by means of a straight edge, and measure the lever arm of each. Calculate the moments of the forces and find their algebraic sum. In addition to finding the sum of the moments about the centre, find also the sum of the moments of the forces about some point outside the

centre. Is the sum of the moments the same wherever the center of moments is taken, or not?

IV. Remove the pivot, so that the disc is free to move in any horizontal direction, and tighten the cords, if necessary. Again read the balances. Make the proper measurements and calculate the sum of the moments of the forces about some point to one side of the centre. Do the same for some point outside of the disc. Is the sum of the moments the same wherever the centre of moments is taken?

V. If any number of forces, in the same plane, act upon a rigid body so that it is held in equilibrium, what do you conclude from the results of this exercise must be the algebraic sum of their moments about any point? The correct answer to this question is called the *Principle of Moments.*

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VI. Definition.—Two equal, parallel forces in opposite directions constitute what is called a *couple*. The perpendicular distance between them is called the *arm* of the couple.

Let $a$ be the arm, and $F$ one of the component forces of a couple. Find the moment of this couple about any point. Is it the same for all points?

## 18. COMPOSITION OF FORCES.

I. Take a stout beam, over a meter long, and find its weight (in lbs.) by means of a spring balance.

Attach cords of equal length to screw-eyes near the ends of the beam, and suspend it by these cords from two 30-lb. spring balances hung from nails in the wall, at the same distance apart as the screw-eyes in the beam. Read the balances. What relation exists between the combined readings of the balances and the weight of the beam?

II. Suspend a mass of metal, weighing over 30 lbs., from the middle of the beam and read the balances again. Do the

balances read alike? Why? How can you find the weight of the metal from the readings of the balances? What is the weight as thus found?

III. Hang the mass of metal from a point to one side of the middle of the beam and read the balances again. Why do they not read alike now? Does the relation found in I between the total suspended weight and the combined readings of the balances still hold true? Measure the distances from the point where the weight is hung to the points where the balances are attached. How do the products of each distance into the reading of the corresponding balance, less one-half the weight of the beam, compare? How might you have anticipated this result from the Principle of Moments? (See Exercise 17, V.)

In general, what is the resultant of two parallel forces in the same direction equal to? what is its direction? and how is its line of action situated with reference to the component forces?

IV. Hang two 30-lb. spring balances from two nails above the blackboard, at least one metre apart, and connect the balances by a cord somewhat over a metre long. From the middle point of this cord suspend the mass of metal used in II and III. Draw on the blackboard lines parallel to the two parts of the cord and lay off on these lines, from their intersection, lengths proportional to the tension in each part of the cord as registered by the proper balance. Construct a parallelogram with these lines as sides and draw the vertical diagonal. Measure the length of this diagonal in lbs., using the same scale as was used for the sides of the parallelogram. How does this diagonal compare in direction and length with the downward force (weight) of the mass suspended from the cord? What is the value of the weight as found by this method?

V. Hang the mass of metal to one side of the middle of the cord, and construct another similar *parallelogram of forces.*

Is the relation between the diagonal and the weight of the suspended mass the same as in IV? What is the value of the weight as found from this parallelogram?

VI. Hang the mass of metal by a single cord from one of the nails. Attach a spring balance to the cord, near the bottom of the blackboard, and pull it horizontally one foot from the vertical. Note the reading of the balance, and measure the vertical distance from the nail to the "line of action" of the horizontal force.

By what two forces was the cord acted upon, and in what direction was their resultant? Which one of these two forces was measured directly? Find the value in lbs. of the other force; as the two forces are at right angles, this may be done either graphically by constructing a *triangle of forces*, or by calculation from similar triangles.

VII. Repeat VI, drawing the cord two feet to one side instead of one foot, and find again the value of the weight.

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VIII. With the arrangement of VI and VII attach another spring balance to the same point on the cord, and pull one of the balances out parallel to the blackboard and the other at right angles to it, so that they both register 10 lbs. Measure (1) the horizontal distance from the vertical line through the nail to the foot of the perpendicular from the point of attachment of the balances upon the blackboard, (2) the length of this perpendicular, and (3) the vertical distance from the nail. From these measurements and the readings of the balances, find the value of the weight in lbs.

## 19. ACTION OF GRAVITY.

NOTE.—The pendulum used in this exercise is a long, flat rod suspended at one end by a hinge so that it can swing freely in only one plane.

I. Fasten a strip of white paper with wax, or an elastic band, to the lower end of a pendulum like the one described and over it a strip of impression paper with its dark surface next to the white paper. Suspend a hard metal ball by a thread passing over a nail just above the pendulum. The ball when lowered and at rest should hang so as just to touch (not rest against) the lower part of the pendulum. This can be accomplished, either by turning the block supporting the pendulum, or, if that is immovable, by hanging the ball from a bent nail and slipping the thread along this nail. Raise the ball to a definite mark near the top of the pendulum. Pass the thread over two other nails (one on the same level as the first and the other below), and fasten the thread to a screw-eye in the pendulum, so as to draw it to one side of the vertical. The friction of the thread against the nails ought to be sufficient to hold the pendulum out. See that the ball hangs opposite the proper mark and everything is in stable equilibrium. Then burn the thread between the two upper nails, so that the ball falls at the same instant that the pendulum is set free and strikes the latter when it reaches the middle of its swing. The ball should strike the impression paper so as to make a mark on the white paper.

Repeat this until two or three marks are obtained in fairly close agreement (that is, within 1 cm., or less, of each other). Measure the height through which the ball falls while the pendulum moves from its extreme to its mid-position. Find the time it takes the pendulum to move this distance, by counting and timing 100 complete vibrations.

Having found the distance fallen through during the time of a half-swing of the pendulum, calculate the average velocity during this time; and from this, the final velocity. (If a body starts from rest and its velocity increases at a uniform rate, the final velocity will be equal to twice the average velocity.)

II. Repeat I with another pendulum of different length,

and find, as in I, the average velocity and the final velocity acquired during the time of a half swing of this pendulum.

III. From a comparison of the results of I and II answer the following:—

1. Is the distance fallen through proportional to the first or to some higher power of the time? What is the power in question?

2. Calculate the distance that the ball would have fallen through in one second starting from rest, using the results of I and II and averaging the two values found.

3. Is the velocity acquired proportional to the first or to some higher power of the time?

4. Calculate the velocity that would have been acquired in one second, using the results of I and of II and averaging the values found. This quantity (the *acceleration* due to the weight) is usually represented by the letter "*g*."

IV. With a suitably graduated spring balance find the weight in dynes of a mass of 200 grammes.

Multiply the mass in grammes by the value of "*g*" found in III. How does the product compare with the weight in dynes as just found?

Given the mass and acceleration (change of velocity in unit time), how in general can the force acting on a body be found?

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V. Repeat I with a ball of different mass. Was the velocity acquired in a half-swing of the pendulum the same as in I?

VI. Repeat I with a ball of about the same size, but of different material. Neglecting the effect of the air, was the velocity found to be dependent in any way on the substance of the falling body?

## 20. THE PENDULUM.

I (*a*). Suspend a metal ball by a thread from a hook near the ceiling. Measure the length from the point of support to

the center of the ball. Lay a rod, or some other "straight edge," under the ball and at right angles to the length of the table, to mark the position of rest. Pull the ball out parallel to the length of the table about 5 cm. from the vertical, and let it go. Find the period,—that is, the time that elapses after it passes the mid-position until it passes it again in the *same direction*,—by counting and timing 100 such complete oscillations. Begin to count "one, two," etc., with the second transit, and note the time of 50 complete oscillations as a check.

(*b.*) Pull the ball out 10 cm. from the vertical and determine the period as in (*a*).

(*c.*) Pull the ball out 20 cm. from the vertical and determine the period as in (*a*).

(*d.*) Were the periods determined in (*b*) and in (*c*) the same as in (*a*)? What was the ratio between the amplitude (one-half the distance swung through) and the length of the pendulum in each case? When the amplitude of a pendulum is less than one-tenth of its length, do you find it to have any appreciable effect on the period?

II. Find the period of the same pendulum when the ball swings over the length of the table, counting and timing 20 or 30 complete oscillations. Measure the mean amplitude, and find its ratio to the length of the pendulum. Is the period the same as in I? Do you find the period of a pendulum to be affected by the amplitude of vibration when the latter is large compared with its length?

III. Replace the metal ball by one of wood of the same size. Lengthen the thread, if necessary, to make the length the same as in I and II. Find the period for an amplitude of 10 or 20 cm. How does it compare with the period found in I with the metal ball? Does the period of a pendulum depend in any way on the mass of the bob when the effect of the air is the same?

IV (*a*). Hang the metal ball by a thread from a stand so

that the length of the pendulum thus formed is one-half that in I, II, and III. Determine the period as in I.

(*b*.) Shorten the pendulum again by one-half and determine its period.

(*c*.) By a comparison of the results of I, IV (*a*), and IV (*b*), find the law connecting the period of a pendulum with its length, assuming that the period varies as some integral root or power of the length.

V. Replace the wooden ball used in III by an iron ball, and shorten the thread, if necessary, so that the ball will just swing over the end of a steel magnet set with its longest axis vertical.

Find the period of the pendulum, with and without the magnet underneath. (In the first case the pendulum should not be swung more than a cm. beyond the magnet.) What saw the effect of the magnet on the period? In what direction was the magnetic force exerted by the magnet on the ball? Would this force have the same effect on the period of the pendulum as a change in the force due to gravity? If so, would the effect be the same as that produced by increasing or by decreasing the force due to gravity?

What do you conclude, from this experiment, would be the effect of increasing or decreasing the force of gravity, upon the period of a pendulum?

## 21. GRAPHICAL MEASUREMENT OF VIBRATION FREQUENCY.

1. Take a sheet of glass, place it under the tuning-fork and pendulum of a tracing apparatus for measuring the frequency of vibration, and adjust the styles attached to them so tha they will just graze the glass.

Smoke the surface of this sheet of glass over a lamp, and replace it under the tuning-fork and pendulum. (The smoking

should be done in the hall, so as not to vitiate the air of the room; and the glass should be kept in constant motion while over the flame, so as not to heat it unequally and cause it to break. Avoid smoking the glass near the edge.) Readjust the styles, if necessary, so that they will remove the lamp-black from the surface of the glass without much friction.

Set the pendulum swinging and the tuning-fork in vibration, by striking it a sharp blow with a rubber hammer, and immediately draw the smoked glass under the styles at right angles to their motion. The style attached to the tuning-fork should trace a wavy line on the blackened surface, crossed at more or less regular intervals by the broken line made by the pendulum style. The glass ought to be moved at such a speed that the pendulum trace will cross the other at least three or four times before it ends. Repeat until a satisfactory result is obtained.

Mark on its trace the successive positions of the tuning-fork style at each instant that its path is crossed by the pendulum style. Do this by measuring the distances between the two styles and laying it off on the tuning-fork trace in the proper direction from the points where the pendulum style crosses. Letter these points *a*, *b*, *c*, etc. Count the number of complete vibrations (estimating fractions, if possible) made by the tuning-fork between *a* and *b*, between *b* and *c*, etc. Are the numbers obtained the same, or alternately larger and smaller? What do you find to be the number of vibrations made by the tuning-fork during a complete oscillation of the pendulum?

II. Find the period of the pendulum by counting and timing 100 oscillations. Calculate, from your results, the number of complete vibrations made by the tuning-fork in a second. This number is called its *vibration frequency*.

What important quality of the note emitted by a tuning-fork is determined by its vibration frequency?

III. Repeat this exercise from the beginning, time permitting, until concordant results are obtained.

IV. Determine, by inspecting the traces obtained in I and III, whether the amplitude of vibration has any appreciable effect on the period of a tuning-fork.

## 22. RESONANCE TUBE.

Description of Apparatus.—The resonance tube to be used consists of a long vertical glass tube connected at its lower end by a rubber tube and siphon with a jar of water, so that when the jar is raised and lowered, the water flows in and out of the tube. The siphon can be started by setting the jar on the floor and pouring water into the tube until it flows into the jar.

I. Hold a vibrating A-fork over the tube, raise the jar, and mark with a rubber band the level of the water when the air in the tube vibrates in unison with the fork and causes a marked increase (a swelling out) in the intensity of the sound.

Lower the jar and, as the water falls, readjust the rubber band to the level of the water when the sound swells out again. Let the water rise and fall past this point a number of times and determine the level when the air in the tube vibrates in unison with the fork as accurately as you can.

As the air has no freedom of motion in a vertical direction at the surface of the water, the plane where the column of air may be cut off without prejudice to its rate of vibration must be one of minimum vibration, *i. e.*, a *nodal plane.*

Find all the prominent nodal planes you can. Measure the distances between them and between the last one and the open end of the tube. Is the latter the same as the distance between two consecutive nodal planes? How are these distances related to the wave-length in air of the particular note sounded?

II. Repeat I with a C-fork, and also with a large G or D-fork.

Find the ratio of the distance between the nodes when the A-fork was used to that when the C-fork was used. This gives the ratio between the wave-lengths. How is this ratio related to the ratio between the vibration frequencies of the two notes? The latter ratio measures the *musical interval* between the notes.

Calculate, from your results, the musical intervals between one of these forks and each of the other two.

III. The velocity of sound in air is given by the formula, $V = 331\sqrt{1 + .004t}$ metres per second, $t$ being the temperature of the air in centigrade degrees. Using the velocity of sound given by this formula, calculate the number of vibrations per second of each of the three forks used.

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IV. Find the length of the column of air that will vibrate in unison with a tuning-fork when it is held over various hydrometer jars. Measure the diameters of these jars. Is the position of the first nodal plane in a resonance tube affected by the diameter of the tube? What does this last experiment seem to show?

V. With the resonance tube and one of the larger forks, try to find, if you can, the nodal planes belonging to the overtones produced. How are these situated?

## 23. PHOTOMETRY.

I. Light a set of four simple gas jets and a single separate jet of the same form, and regulate the flow of gas so that the jets are all of the same height and brightness. Set a diffusion photometer,—two rectangular blocks of paraffine separated by a sheet of tin-foil,—so that the two blocks of paraffine are

equally illuminated by the diffused light of the room. Place the single jet at a distance of 50 cm. on one side of the photometer, so as to illuminate one block of the paraffine, and the set of four jets on the other side at such a distance that the two blocks of paraffine will be equally illuminated. Measure the distance from the photometer to the four jets.

How does the illumination of the paraffine due to the single jet compare with that due to the four jets? How does the intensity of the illumination due to a single jet at 50 cm. compare with that due to a *single* jet at the distance of the four jets? The intensity of the illumination is proportional to an integral power of the distance; what, from your results, do you conclude to be the power in question? Is it direct or inverse?

II. Place the four jets at 50 cm. from the photometer and the single jet on the opposite side at such a distance that the blocks of paraffine are again equally illuminated. Are the conclusions drawn from the results of I corroborated or not, by the results thus obtained?

III. Light a candle and place it at a certain distance from the photometer. Light a coal-oil lamp and place it on the opposite side of the photometer, so that the candle and lamp illuminate the blocks of paraffine equally. (The height of the lamp wick should not be altered during the course of this experiment.) How can you find the ratio between the illuminating power of the candle and that of the lamp? What is this ratio as derived from your measurements? Repeat the latter until you are sure of your result.

Weigh the lamp and the candle. Let them burn for 30 minutes or so. Reweigh and find the mass of the coal-oil and of the paraffine* consumed. For one gramme of matter consumed by the candle, how many grammes were consumed

*The word "paraffine" is used in this and the next paragraph for the substance of the candle, whatever it may be.

by the lamp? Calculate the relative illuminating power of coal-oil and paraffine for equal masses (or weights) consumed, assuming that the illuminating power varies directly as the amount of matter consumed.

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IV. Alter the height of the lamp flame and repeat III. Calculate again, from the results obtained, the relative illuminating power of coal-oil and paraffine for equal masses consumed. How does the value found compare with that found in III? Is the assumption made above, that the illuminating power varies directly as the amount of matter consumed, corroborated by the results of III and IV, or not?

V. Remeasure the "candle-power" of the lamp in IV by means of a Rumford shadow photometer, instead of the diffusion photometer. (Ask for apparatus and necessary directions.)

## 24. REFLECTION AND REFRACTION OF LIGHT.

I. Laws of Reflection.—A board is fastened to the edge of a table so that a straight line ruled on it is perpendicular to the surface of the table. Take a plane mirror with a line scratched on its back perpendicular to one edge and lay it on the table with this edge against the vertical board, so that the lines on the board and on the mirror meet. Attach pins to the upper edge of the board at distances of 5, 10, and 15 cm. from the vertical line. Place your eye so that the image of the first pin in the mirror appears to coincide with the line ruled on the back of the mirror. Measure the horizontal distance from the vertical line to the point where the reflected ray crosses the upper edge of the board.

Repeat this with each of the other pins. How does the horizontal distance of the incident ray, in each case, from the vertical compare with that of the reflected?

The *angle of incidence* is the angle between the incident ray and the normal to the reflecting surface, and the *angle of reflection* is the angle between the reflected ray and the normal. What is the relation between the angle of incidence and that of reflection, as deduced from this experiment?

Is the plane containing the incident and reflected rays normal to the reflecting surface, or not? Find the answer to this question by experiment, choosing your own method and describing it fully.

II. Laws of Refraction.—Take a rectangular vessel with high sides and partially fill it with water, at the same time wedging up the corners so that the surface of the water will be level with a mark on one side and also with a horizontal wire across the vessel. Transverse lines one centimeter apart are drawn on the bottom of the vessel, the first line being in the vertical plane through the horizontal wire, and a line is also drawn on the side to mark the position of this vertical plane. Place your eye so that the second line on the bottom, as seen through the water, appears to coincide with the horizontal wire at the surface. Without moving your eye, locate the intersection of the emergent rays with the horizontal plane through the top of the vessel by means of a thin straightedge, as a strip of paper, stretched across the top of the vessel. Measure its distance from the vertical line on the side of the vessel.

Repeat this for each of the other lines on the bottom of the vessel. Measure the depth of the water and the distance from its surface to the top of the vessel. Are these two distances equal or nearly so? Are the distances of the lines on the bottom of the vessel from the vertical the same as the corresponding distances of the emergent rays from the vertical? If they are not, how do you account for the difference?

The ratio of either side of a right triangle to the hypothenuse measures a function of the angle opposite the side con-

sidered called in trigonometry the "sine" of the angle. Calculate from your measurements the sine of the angle of incidence, and of the corresponding angle of refraction for each case.

The ratio of the sine of the angle of incidence to that of the angle of refraction when the light is incident in air,—or more properly in a vacuum,—is called the *index of refraction* of the substance. (If the light is incident in the substance and refracted in air, the index of refraction, on the contrary, is equal to the ratio of the sine of the angle of refraction to that of the angle of incidence.) Calculate from your results, the index of refraction of water. Do you find it approximately the same for all angles of incidence, or not?

Observe whether the plane containing the incident and refracted rays is normal to the surface, or not.

III. Image in a Plane Mirror.—Clamp the mirror used in I to a stand with its plane vertical. Place an upright rod about 20 cm. in front of the mirror, and another rod behind it so as to coincide with the image of the first rod. This can be done by changing the position of the observer's eye and adjusting and readjusting the position of the second rod until it will always coincide in direction with the image of the first rod from every point of view. Measure the distance between the mirror and the object, and also between the mirror and the image. What do you find to be the relation between the position of an object and the position of its image in a plane mirror?

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IV. From the laws of reflection found in I, prove your answer to the last question of III by a simple geometric construction.

## 25. IMAGES IN A SPHERICAL MIRROR.

I. Place a concave spherical mirror so as to form as clear an image as possible of the window bars on a screen, and measure the distance from the mirror to the screen.

Repeat, using some distant object, as the tops of the trees across the road, instead of the window bars, and measure again the distance from the mirror to the screen. Was this distance greater or less than when the window bars were focused on the screen? The *principal focus* is the point through which all parallel rays are reflected. Its distance from the mirror is called the *principal focal length* of the mirror. Which of the measurements above may be taken as the principal focal length of the mirror?

II. Place an upright rod at a distance from the mirror equal to twice its principal focal length. Adjust the positions of the mirror and rod by the "method of parallax," used in Exercise 24 to find the position of an image in a plane mirror, so that some definite point on the rod will exactly coincide in position with its image in the mirror. To do this, adjust the rod first so as to coincide with its own image, and then slide a piece of paper up or down the rod until it meets its own image. This will give the required point on the rod. (Do not confound the image formed by the front, plane surface of the glass with that formed by the spherical mirror on the back.) What measurement will now give the radius of curvature of the mirror? Why? How does this compare with the principal focal length?

III (*a*). Place the screen at as great a distance from the mirror as the table will allow, and place two gas jets so that their images formed on the screen will be as distinct as possible. To obtain images beyond the center of curvature of the mirror, where did the gas jets have to be placed, between

the mirror and the principal focus, between the principal focus and the center of curvature, or beyond the center of curvature?

(*b.*) Measure the distance from the mirror to the gas jets and the distance from the mirror to the screen; also the distance between the gas jets and between their images. How does the ratio between the first two distances compare with the ratio between the last two? Substitute the distances from the center of curvature of the mirror for the distances from its surface. Is the ratio changed?

(*c.*) Reduce to decimals the reciprocals of (1) the distance from the mirror to the gas jets; (2) the distance from the mirror to their images; (3) the principal focal length; (4) the radius of curvature. Of these four reciprocals find two whose sum is equal to a third, and also equal to a simple multiple of the fourth.

IV. Interchange the positions of the gas jets and the screen. (In the new positions they will of necessity have to be placed on opposite sides of a line normal to the mirror.) Adjust the screen so as to obtain as definite images as possible, and repeat the measurements of III (*b*). Does the proportion found in III (*b*) still hold true? Does the relation between the reciprocals in III (*c*) still hold true? When the gas jets are beyond the center of curvature, are the images formed between the mirror and the principal focus, between the principal focus and the center of curvature, or beyond the center of curvature?

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V. Place a vertical rod between the mirror and its principal focus, within 8 or 10 cm. of the mirror, and locate its image by means of another rod, using the method of parallax. Measure the distance from the mirror to the object and its image respectively. In order that the relation between the reciprocals found in III (*c*) shall still hold true, what change in sign is necessary?

VI. Suppose an object at an infinite distance from the mirror; where would its image be found, and how would it change in position as the object approached the mirror, supposing the object to approach until it touched the surface of the mirror? State whether the image would be real, or virtual; erect, or inverted; larger than the object, or smaller.

## 26. CONVEX LENSES.

I (*a*). With a convex lens form an image of the window bars on a screen and measure the distance from the lens to the screen.

(*b*.) With the same lens form an image of some distant object on the screen, and measure again the distance from the lens to the screen. Is this distance the same as in (*a*)? Which of these distances may be taken as the principal focal length of the lens?

II. Light two gas jets and place them at a distance from the lens equal to twice its principal focal length, and place the screen so as to form as distinct images of the jets as possible. Measure the distances respectively from the lens to the screen, and from the lens to the gas jets. How do these distances compare? Measure the distances between the gas jets and between their images. How do these distances compare?

III. Set the gas jets at a distance from the lens equal to about five times its principal focal length, and place the screen so as to form as distinct images as possible of the jets.

Measure the distances: (1) From the lens to the screen; (2) from the lens to the gas jets; (3) between the gas jets; (4) between their images. Find a relation existing between these quantities and express it in the form of a proportion.

Reduce to decimals the reciprocal (1) of the principal focal length; (2) of the distance of either gas jet from the lens;

(3) of its image from the lens. The sum of what two of these reciprocals is approximately equal to the third?

IV. Interchange the position of the gas jets and the screen and adjust the lens, if necessary, so as to make the images as distinct as possible. Repeat the measurements of III.

Form a proportion, if you can, similar to that formed in III, and find, if you can, a similar equation connecting certain reciprocals.

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V. Set an upright rod between the lens and the principal focus. On which side of the lens is the image of the rod? Is the image real, or virtual; erect, or inverted? Locate this image by means of another upright rod, by the method of parallax already used in Exercise 24, III, and in Exercise 25, II. In order that the relation between the reciprocals previously found should still hold true, what change in sign is necessary?

VI. Answer the following questions as applied to a convex or converging lens:—

1. Where should an object be placed in order that its image may be real? In order that its image may be virtual?

2. When will the image be erect, and when inverted?

3. Where should the object be placed in order to form an enlarged image? In order to form a diminished image?

4. Where should the object be placed in order to use a converging lens as a magnifying glass?

## 27. CONCAVE LENSES.

I. Locate with an upright rod the image formed by a concave lens of some vertical part of the window sash, using the method of parallax. (The rod used in locating the image should be looked at *over* not *through* the lens.) Measure the distance from the lens to the image.

Locate, in the same way, the image of some vertical object in the distance, as the corner of a house, or a telegraph pole, and find the principal focal length of the lens.

How do these images formed by a concave lens compare, as regards position and size, with the images of the same objects formed by a convex lens? [See Exercise 26, I (*a*) and (*b*).]

II (*a*). Place the vertical rod at a distance from the lens equal to about twice its principal focal length, and locate its image by means of another vertical rod. Measure the distance from the lens to the image.

(*b*.) Repeat with the stationary rod at the principal focus.

(*c*.) Repeat with the stationary rod between the principal focus and the lens.

Compare the relative positions of the image and object in each of these cases with the similar cases when a convex lens was used. (See Exercise 26, II and V.)

Reduce to decimals the reciprocal (1) of the distance from the lens to the image in either (*a*), (*b*), or (*c*); (2) of the corresponding distance from the lens to the object; (3) of the principal focal length. Which one of these distances should be made negative in order that the sum of the first two reciprocals should be equal to the third?

III. Set two vertical rods attached to the same support at a suitable distance from the lens (to be determined by the student), and locate their images by means of two other separate rods.

Measure (1) the distance of the fixed pair of rods from the lens, (2) the distance of their images from the lens, (3) the distance between the rods, and (4) the distance between their images. Do you find the proportion found in Exercise 26, III and IV, for a convex lens to hold true for a concave lens?

IV. Answer the following questions:—

1. Can a real image be formed by a concave lens?

2. Can a concave lens be used as a magnifying glass?

3. Suppose an object at an infinite distance from a concave lens; where would its image be located, and how would it change in position as the object approached the lens, supposing the object to approach until it touched the lens?

4. Can there be such a thing as a real and erect image, or a virtual and inverted image?

V. Ask for and fill out a blank table to accompany this exercise. Leave the completed table with the instructor.

## 28. DRAWING SPECTRA.

General Directions.—Place a spectroscope so that none of the diffused light of the room will enter its slit, and set a Bunsen flame directly in front of the slit. Before examining the spectrum of a salt, scrape a platinum wire and hold it in the heated part of the flame until all traces of other salts disappear. Dip the wire, while red-hot, into the salt to be examined, so as to fuse some onto the wire. If the salt is volatile, hold the wire in the lower edge of the flame; but if refractory, hold it in the hottest part of the flame. Hold the wire so that the colored part of the flame is opposite the slit, but do not hold the incandescent wire itself opposite the slit. In general, the narrower the slit the more distinct the spectrum; but for potassium and thick blue glass the slit will have to be widened.

I. Dip the wire into a sodium salt, and hold it in the flame. Narrow the slit and adjust the focus of the telescope so as to obtain as sharp an image of the slit as possible. Then by moving the scale in or out bring it (the scale) also to a sharp focus. Set the scale so that the yellow sodium band will coincide with the division marked 5 (or 50).

Make a copy in your note-book of the spectroscope scale, and draw on it long lines corresponding in position to the

bands in the spectrum of the salt. Indicate the color of these bands, and also note the general color of the flame.

II. Draw, as in I, the spectra of salts of potassium, calcium, strontium, lithium, barium, and boron (boracic acid). State in each case the general color of the flame. A trace of sodium is apt to be present in the flame, but its spectrum can be easily distinguished from that of the salt under examination.

III. Draw the spectrum of a luminous flame, and also of the same flame seen through plates of red, green, yellow, and blue glass. Is the light transmitted by any of these plates monochromatic (of one wave length), or not?

## 29. LAWS OF MAGNETIC ACTION.

PROPOSITION.—If a compass-needle is deflected by a horizontal force acting in an east and west direction, the magnitude of the force will be proportional to the tangent* of the angle of deflection. (Ask for the proof of this proposition.)

I. Place two pocket compasses side by side. Do the like poles attract or repel each other? Do the unlike?

II. Hold a long, magnetized clock spring in a vertical position against the east or west side of a table, so that its extreme end will be about an inch above the table. Mark off on the table, on a line drawn east and west through the axis of the magnet (the clock spring), points at distances of 10, 15, 20, 30, and 40 cm. from the magnet. With a pair of dividers, draw a circle about one inch in diameter around each of these points as a center. Set a pocket compass within the first circle, so that its center is 10 cm. from the stationary magnet. Remove the latter to some distance, and adjust the compass so that its needle reads zero degrees. (The compass should

* The "tangent" is a function of either oblique angle of a right triangle measured by the ratio of the side opposite the angle to that adjacent.

be tapped very lightly as it comes to rest, with the finger or with a rubber pencil-tip.) Replace the magnet against the side of the table, and read the deflection of the compass-needle. (Tap the compass as before, and read both ends of the needle, averaging the results.) To what is the horizontal component of the force exerted by the magnet at the center of the needle proportional? (See "Proposition" above.)

III. Repeat the last part of II with the compass-needle at 15, 20, 30, and 40 cm., respectively, from the stationary magnet. Calculate from your results (using a table of natural tangents) the ratio of the horizontal force due to the magnet at 10 cm. to that at 20 cm.; at 15 cm. to that at 30 cm.; at 20 cm. to that at 40 cm., etc. Does the force vary directly, or inversely with the distance? Assuming that it varies (directly or inversely) as some integral power of the distance, what do you find to be the power in question?

IV. Take a comparatively short magnet and lay it on the table on a line drawn east and west through the center of a compass-needle, at such a distance as to deflect the needle about 40°. Read the deflection and measure the distance from the center of the magnet to that of the compass-needle. Place the magnet at double this distance, and read the deflection again. Do you find the horizontal force to vary with the distance in this case according to the law found in III, or not? Was the needle in II and III acted on in a horizontal direction by both poles of the magnet, or practically by one alone? Was it in IV?

When a magnet is comparatively short, how do you find the force exerted by it at any point to vary with distance of the point from the center of the magnet, assuming that it varies as some exact integral power of this distance?

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V. What is the force between two magnetic poles at the

distance $d$ apart, the strength of the poles being $m_1$ and $m_2$ respectively? (For definition of "pole strength" see Exercise 31, V, Question 3.)

## 30. MAGNETIC FIELDS.

I. Take a magnet 16.5 cm. long, and locate approximately the mean distance of either pole from the end, by the following method:—

Lay the magnet on a sheet of paper, and trace its outline with a pencil. Place a compass on the paper so that the compass box is about one cm. from the magnet. Commencing near the end of the magnet, move the compass, one or two cm. at a time, parallel to the magnet, drawing, for each position of the compass, lines to indicate the direction of its needle. Remove the magnet, draw a line through the position of its axis, and extend the above lines until they intersect this line. Find a median point and measure its distance from the end of the magnet.

II. Lay the magnet used in I lengthwise on a large sheet of brown paper. Draw the outline of the magnet with a pencil, and sprinkle iron filings on the paper around it. Trace the lines in which the iron filings set themselves when the paper is tapped.

Brush the iron filings off the magnet, and return them to the sprinkler, taking care not to scatter and waste them. (In removing iron filings from a magnet, brush them towards the center, and not towards the ends.)

Replace the magnet, and place a small compass at different points of the tracing. How does the direction of the compass-needle at any point coincide with that of the lines of iron filings?

III. Take a sheet of cardboard and place it with its sides parallel to the edges of the table. To the most northerly or

southerly corner of the cardboard fasten a small compass with wax* and, after removing all magnetic substances from the neighborhood, draw a pencil line to correspond with the magnetic meridian through the compass. On this line place a short magnet with its north pole directed toward the south, and adjust the distance between it and the compass so that the compass-needle is in neutral equilibrium (*i. e.*, will point indifferently in any direction). Fasten the magnet in this position to the cardboard with wax. The compass-needle will not be affected now by the earth's magnetic field while the sides of the cardboard are parallel to the edges of the table.

IV. Take the drawing made in II. Mark the position of the poles of the magnet, and draw a circle, about 2 or 3 cm. in diameter, around each. Divide these circles into 12 or more equal parts, and through each division draw a line, following the directions in which the iron filings set themselves, as far as these directions can be determined.

Replace the magnet on the paper, and place the compass-needle, protected as in III from the influence of the earth's magnetic field, at the end of one of these lines. Extend this line an inch or so in the direction indicated by the needle. Prolong all the lines through the divisions of the circle in this way, an inch or so at a time, as far as the limits of the paper will allow.

V. Take a point on one of these lines about 9 or 10 cm. from one of the poles of the magnet, and 12 or 15 cm. from the other pole. Suppose a north or south magnetic pole to be placed at this point. Draw lines in the directions that this pole would be urged by each pole of the magnet, and lay off on these lines distances proportional to the forces in these directions due to the poles taken separately. (See law found

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* Attach the wax to the edge of the compass, and *do not put it underneath.*

in Exercise 29, III.) Construct on these lines a parallelogram of forces, and find the direction of the resultant force due to both poles of the magnet. How does the direction of this resultant compare with that of the magnetic line of force at the point considered?

If it were possible to produce an isolated north magnetic pole and place it in a magnetic field, how would the path along which it would move be related to the magnetic lines of force? Deduce from this a definition of a *magnetic line of force.* How is the strength of the magnetic field due to the magnet indicated by the lines of force at any point in the preceding diagram?

The sheet of brown paper used in II, IV, and V should be signed and handed in with the other notes.

VI. Lay two short magnets on a sheet of white paper with impression paper and another sheet of white paper underneath (or they may be laid directly on a page of the note-book). Lay them parallel, side by side, about 1.5 or 2 cm. apart, with their unlike poles opposite. Sprinkle iron filings about them, and trace the lines along which the filings set themselves.

VII. Repeat VI with the magnets placed so that their like poles are opposite.

VIII. Hold a single magnet vertically with its lower pole resting on the paper. Sprinkle iron filings about it, and trace the lines of force due to a single magnetic pole.

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IX. Take another large sheet of brown paper, and lay a magnet on it in an east and west direction. With a compass-needle plot, as directed below, the resultant field due to the earth and the magnet, and indicate any neutral points that may be found.

In tracing a line of force, place the compass near the magnet, and make two marks at the ends of the needle, to show its position; then remove the compass, and mark the middle

point. Replace the compass so that the south (or north) end of the needle is where the north (or south) end was before; mark the position of the other end of the needle, and find the middle point again. Continue this until the limits of the paper are reached, and draw a curved line connecting the middle points found.

## 31. EARTH'S MAGNETIC FIELD.

I. The west and east edges of the table, if they are parallel to the walls of the building, are directed 16° west of the true north (*i. e.*, of the meridian passing through Berkeley). Place a compass so that the diameter passing through the division 16° west c the north and south line is parallel to the west (or east) edge of the table. What line indicates the direction of the true north? Why does the needle not point in this direction? Is the deviation of its north end toward the east, or the west? What angle does the needle make with the true north? This angle is called the *declination* of the needle.

II. Place a compass on the table and draw a line through its center in the direction of the magnetic meridian. Draw another line through the center of the compass at right angles to this line. On the latter, east of the compass, place a magnet similar to the one used in Exercise 30, I, at such a distance that the compass-needle is deflected through an angle of 45°. Measure the distance from the end of the magnet to the center of the compass-needle.

III. Repeat II with the poles of the magnet reversed.

IV. Repeat II and III with the magnet west instead of east of the compass.

V. Average the four distances* measured in II, III, and IV, and answer the following questions:—

* The object of these reversals of position and direction is to eliminate all errors due to irregular distribution of magnetism in the magnet, and in drawing the east and west line.

1. How does the horizontal force at the center of the compass due to the magnet, in each of the four cases, compare with that due to the earth's magnetism?

2. What is the mean distance of the nearer pole of the magnet? Of the farther pole? (Use the position of the poles found in Exercise 30, I.)

3. Calling the "pole strength" of the magnet *P*,—defined as the force exerted by the pole of the magnet on a unit magnetic pole* at a distance of one cm.,—calculate in terms of *P*, from the law deduced in Exercise 29, III, the force exerted by the nearer pole of the magnet on a unit pole at the center of the needle; by the farther pole. What is the intensity of the resultant field (*i. e.*, the force on a unit magnetic pole) at the center of the needle due to both poles of the magnet?

4. How does this compare with the horizontal component of the earth's magnetic field at this point? (See question 1, above.)

VI. Having found the horizontal component of the earth's magnetic field at a point on the table in terms of *P*, the pole strength of the magnet, find *P* by substituting for the horizontal component its approximate value, 0.24 dynes.

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VII. The ratio of the horizontal component of the earth's magnetic field to the total field (*i. e.*, the force on a unit pole in the direction of the dipping needle) is equal to the cosine of the angle of dip or the sine of 90° minus the angle of dip. Prove this relation by a triangle of forces.

Taking 0.24 dynes for the horizontal component of the earth's magnet field and 62½° for the angle of dip, calculate by means of the above relation, the total field due to the earth's magnetism.

VIII. Find the declination and intensity of the earth's magnetic field on other tables in the room.

*A unit magnetic pole is a magnetic pole of such strength that it will exert a force of one dyne on a similar pole at the distance of one cm.

## 32. ELECTRO-MAGNETIC RELATIONS.

I. Connect the plates of a Daniell cell by a flexible wire cord. Stretch a portion of this cord out straight and hold it near a compass-needle placed on the edge of a low wooden block. The electric current is supposed to flow through the external circuit from the copper plate of the cell to the zinc plate. In what direction is the north pole of the compass-needle deflected, or is it deflected at all, when the current and the needle are in the following relative positions:—

1. Current flowing north, needle below?
2. Current flowing north, needle above?
3. Current flowing north, needle east or west?
4. Current flowing south, needle below?
5. Current flowing south, needle above?
6. Current flowing south, needle east or west?
7. Current flowing upward, needle north?
8. Current flowing upward, needle south?
9. Current flowing downward, needle north?
10. Current flowing downward, needle south?
11. Current flowing east or west, needle above or below?
12. Current flowing east or west, needle north or south?

II. Answer the following questions:—

1. How is the compass-needle affected by reversing the direction of the current?

2. How is it affected when its position is changed from one side of the current to the other?

3. What do you find to be the direction of the force exerted by an electric current upon a magnetic pole with reference to the direction of the current, and of a line from the pole perpendicular to the current?

4. Suppose the current is represented in position and direction by the fingers of the right hand and the palm to be

turned towards the compass-needle, which pole would be deflected in the direction indicated by the thumb in I, 1; in I, 2; in I, 3; etc.?

5. Why was not the needle deflected in I, 3 or 6; in I, 11 or 12?

III. Connect the plates of the Daniell cell to a rectangular coil suspended with its terminals in mercury cups so as to turn freely about a vertical axis. Set the coil with its plane north and south. Follow the path of the electric current from the copper plate of the cell through the coil to the zinc plate, and find in what part of the coil the current flows in a northerly direction, in what in a southerly direction, in what part upward, and in what part downward.

Take a magnet and hold its north pole in the following positions relative to the current, observing in each case the direction in which the current tends to move:—

1. Current flowing north, north pole below.
2. Current flowing north, north pole above.
3. Current flowing north, north pole east or west.
4. Current flowing south, north pole below.
5. Current flowing south, north pole above.
6. Current flowing south, north pole east or west.
7. Current flowing upward, north pole north.
8. Current flowing upward, north pole south.
9. Current flowing downward, north pole north.
10. Current flowing downward, north pole south.

How does the force exerted by a magnetic pole upon an electric current compare in direction with that exerted by the current upon the pole? (Compare the results of I and III.)

IV. Take a suitably mounted annular coil, and connect it to the storage battery terminals. Place a piece of paper on a plane surface perpendicular to the coil through its center and make a pencil tracing of the magnetic field due to the coil,

using iron filings as in Exercise 30. (Disconnect the terminals of the storage battery when through, so as not to waste its energy.)

What form do you find the lines of magnetic force to take about a wire conveying a current?

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V. Trace, by means of iron filings, the magnetic field due to a helical coil conveying an electric current. How does this compare with the field due to a long magnet? (See Exercise 30, II.)

VI. Trace in the same way the field due to a flat coil in a plane parallel to that of the coil.

## 33. LAWS OF ELECTRO-MAGNETIC ACTION.

I. Take a piece of insulated wire and bend it into a circle about 24 cm. in diameter, leaving two ends of about equal length, which should be wound around each other, so that the effect of an electric current in one will be neutralized by that of an equal and opposite current in the other. Clamp this circular coil to the side of a wooden block. Place a compass-needle on the block at the center of the coil, and set the block so that the magnetic meridian is in the plane of the coil.

Connect this rude galvanometer with some source furnishing a constant electric current, as a storage battery. Read the angle of deflection of the compass-needle. Reverse the direction of the current and read the angle again. Average the two results.

In what direction is the force tending to deflect the needle? (See Exercise 32.) To what function of the angle of deflection is this force proportional? (See Exercise 29, Proposition.)

II. Double the coil used in I so as to reduce its diameter one-half without altering the length of wire in the coil. Pass

the current through it again and read the angle of deflection of the compass-needle, reversing the current and averaging the east and west deflections as was done in I.

III. Repeat II with a coil of the same diameter but having twice the length of wire as in II, *i. e.*, having twice as many turns of wire.

IV. Set up three such rude galvanometers having coils of the same diameter and length, placing them as far apart as the table will allow, and connect them so that the whole current passes through one coil and half of the current through each of the other coils. Read the angle of deflection of each compass-needle. Reverse the direction of the current and average the east and west deflections of each galvanometer.

V. Answer the following questions:—

1. How does the force at the center of a circular coil carrying an electric current, vary with the diameter or radius of the coil, according to the results of I and II, assuming that it varies with some integral power (direct or inverse) of the diameter?

2. How, with the length of wire in the coil, according to the results of II and III?

3. How with the current, according to the results of IV?

Assuming that the force $F$ on a unit magnetic pole at the center of a circular coil depends only on the length, $L = 2\pi RN$, of wire in the coil, its radius, $R$, and the current, $C$, express this force in terms of these three quantities and a constant, $K$.

## 34. TESTING AN AMMETER.

I. Connect a rude tangent galvanometer, similar to those used in Exercise 33, in series with a storage cell and an ammeter. Place the instruments as far apart as the table will allow, and read the deflection of each. (Tap the ammeter as

well as the galvanometer and be sure that their needles are free when they come to rest.)

Interchange the battery connections so as to reverse the current through both instruments, and read them again. Take the average of the readings before and after reversing the current. What source of error is eliminated in this way?

II. Reverse the direction of the current through the ammeter and repeat I. Take the mean of the average readings found in I and in II. How is the mutual action of the two instruments eliminated in this way?

III. Repeat I and II with about 50 cm. of No. 25 German silver wire included in the circuit. What is the effect of this wire on the readings of the ammeter and the galvanometer?

IV. In Exercise 30 an equation was found connecting the force, $F$, on a unit magnetic pole at the center of a coil conveying a current with the intensity of the current, $C$, the radius of the coil, $R$, the length of the wire in the coil, $L = 2\pi RN$, and a constant, $K$. The C. G. S. unit of current in the electro-magnetic system of units is the current that will exert a force of one dyne on a unit magnetic pole at the center of an arc one cm. long, of one cm. radius. If $C$, in the equation found in Exercise 33, was measured in terms of this unit, $F$ in dynes, and $R$ and $L$ in cm., what will be the value of $K$? (Find by making $F$ equal to 1 dyne, $R$ equal to 1 cm., $L$ equal to 1 cm., etc.) Having rid the equation of the constant $K$, find the value of $C$ in terms of the other quantities, $F$, $R$, and $L$.

If $H$ is the horizontal component of the earth's magnetic field and $\theta$ the angle of deflection of the needle, we have $F = H \tan \theta$. (Ask for the proof of this equation, if you cannot prove it yourself.) Substitute this value of $F$ in the equation found above and thus obtain an expression for the current through a tangent galvanometer, in C. G. S. units, in terms of four measurable quantities, viz., the radius of the coil,

$R$, the length of wire in the coil, $L=2\pi RN$, the horizontal component of the earth's field, $H=.24$ dynes on a unit magnetic pole, and the tangent of the angle of deflection, $\theta$.

Measure the radius of the galvanometer coil and its length. Calculate, by means of the equation just found, the current in C. G. S. units through the galvanometer circuit in I and II; also in III. How do the results compare with the readings of the ammeter?

The ammeter is designed to read the current directly in "amperes,"—the unit of current in practical use. What, from your results, do you find to be the ratio between the C. G. S. unit of current and the ampere?

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V. Alter the current, by introducing more or less German silver wire into the circuit, and test the accuracy of the ammeter scale in various parts, as far as time permits.

## 35. ELECTRICAL RESISTANCE.

Directions for Using the Ammeters.—In setting up an ammeter turn it so that the plane of the coil contains the magnetic meridian, and level it so that the needle swings freely. (The latter condition can be tested by deflecting the needle with a knife blade or steel key and observing its motion.) If there are two ammeters in use on the same table, they should be set at least 100 cm. apart. Any wire carrying a current in the immediate vicinity of an ammeter should be laid near and parallel, if possible, to another wire carrying an equal current in the opposite direction, so as to eliminate its effect on the needle.

In using an ammeter, or any other kind of galvanometer, always read the scale at both ends of the pointer, reverse the current, read at both ends again, and average the four read-

ings to find the true reading. In this way all errors due to eccentricity of the circle with respect to the needle, to imperfect orientation of the coil, and to dissymmetry in the construction of the needle are completely eliminated. The instrument should also be jarred gently as the needle comes to rest.

I (*a*). Connect an ammeter directly with the storage battery terminals and read the current.

(*b*.) Introduce 50 cm. of No. 25 German silver wire into the circuit in series with the ammeter. (Use a specially constructed rheostat, with stretched wires of various sizes and a movable connection.)

Read the current. How was its value altered, if any, by introducing this wire into the circuit?

(*c*.) Repeat with 100 cm. of No. 25 German silver wire. What is the effect on the current of doubling the length of German silver wire in the circuit?

If we consider that the wire offers a certain kind of *resistance* to an electric current, and assume that the resistance varies as some integral power of its length, what do the results of (*b*) and (*c*) show this power to be? Is it direct, or inverse?

II (*a*). Repeat I (*c*) with two No. 25 German silver wires, each 100 cm. long, connected "in parallel," instead of the single wire. What is the effect upon the current of paralleling the resistance wire with another wire of the same material and of equal diameter and length? [Compare the results of I (*c*) and II (*a*).]

(*b*.) Adjust the length of the two wires, if necessary, so that the current through the ammeter is the same as in I (*b*). How does the resistance of the two wires in parallel, after this adjustment, compare with the resistance of the single wire in I (*b*)? How do their lengths compare? What do you find to be the ratio of the resistance of a single wire to

that of two wires of the same material, length, and diameter connected in parallel?

III (*a*). Connect a No. 25 German silver wire 20 cm. long in series with the ammeter and read the current.

(*b*.) Replace the No. 25 German silver wire by a No. 20 German silver wire of the same length, and measure the current again. What do you find to be the effect of increasing the cross-section of a wire upon the current? [Compare III (*a*) and III (*b*).]

(*c*.) Adjust the length of the No. 20 German silver wire so that the current through the ammeter is the same as in III (*a*). How does the length of the No. 20 wire compare with that of a No. 25 wire having the same electrical resistance? [See III (*a*).]

(*d*.) With a screw gauge, or vernier calipers, measure the diameter of the No. 25, and also of the No. 20 wire. What is the ratio of the diameters of the two wires? What is the ratio of the resistance of a No. 25 wire to the same length of No. 20 wire, as deduced from the results of III (*a*) and III (*c*)? Assuming that the electrical resistance varies as some integral power of the diameter of a wire, what do you find the power in question to be? Is it direct or inverse? How must the resistance vary then with the cross-section of the wire? How do the results of II (*b*) confirm your answer to this last question?

IV (*a*). Introduce 50 cm. of No. 25 brass wire into the circuit, instead of the German silver wire, and measure the current. Do you find the resistance of brass wire to be the same as that of German silver wire? [Compare I (*b*) and IV (*a*).]

(*b*.) Replace the brass wire by the No. 20 German silver wire and adjust its length so that the current through the ammeter is the same as in IV (*a*).

Having found a certain length of No. 20 German silver

wire equal in resistance to 50 cm. of No. 25 brass wire, and knowing the diameters of these wires, calculate the relative resistances of brass and German silver wires of the same diameter and length.

V (*a*). Connect a coil of fine insulated copper wire wound on a strip of wood in series with the ammeter and storage battery. Read the current through the ammeter.

(*b*.) Place the coil for a few minutes in a kettle of boiling water. Read the current again. What effect did the heating of the coil have upon the current? Did the heating of the copper increase or decrease its electrical resistance?

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VI (*a*). Replace the coil of copper wire by two plates of sheet copper held together by rubber bands and separated by strips of wood, or ebonite. (The plates should be washed thoroughly at the sink before being used.) Place the plates in a vessel of water fresh from the faucet and read the current through the ammeter, if there is any.

(*b*.) Dip the same plates into water containing copper sulphate in solution and read the current again. Do you find the addition of copper sulphate to have any effect on the electrical resistance of the water? Was the electrical resistance increased or decreased?

VII. Repeat IV with iron wire instead of brass.

VIII. Repeat IV with fine copper wire instead of brass.

## 36. ELECTROMOTIVE FORCE.

I (*a*). Connect a low-resistance galvanometer (an ammeter) directly to a Daniell cell and note the reading. Introduce another Daniell cell into the circuit in series with the first cell, with the copper plate of one cell connected to the zinc plate of the other, so that the currents due to both flow

in the same direction through the ammeter. What change did the second cell produce in the reading of the ammeter, if any?

(*b*.) Repeat the whole of (*a*) with a high-resistance galvanometer, constructed so that the effect on the deflection due to diminishing the current is offset by having a great length of wire in the coil. How did the change in the reading produced by introducing an additional cell into the circuit compare with that produced by the additional cell when an ammeter was used? Should a galvanometer of high, or low resistance be used to show the effect of connecting two battery cells in series?

The effect of connecting two cells in series is to double the *electromotive force* tending to produce an electric current in the circuit. What sort of a galvanometer (high- or low-resistance) do your results indicate should be used to measure the electromotive force due to any source of electric currents or between two points of a circuit carrying a current? What is the objection to using a high-resistance galvanometer to measure the current flowing through a circuit? Would the current be the same after introducing such a galvanometer into the circuit as before?

The practical unit of electromotive force is called a "volt," and a high-resistance galvanometer graduated to give the electromotive force between its terminals in volts is called a "voltmeter." The instruments of this class used in (*b*) were designed for use as voltmeters and will be designated as such hereafter.

II. With a voltmeter measure the electromotive force of the following cells and combinations of cells, and answer the questions asked. (The directions for using an ammeter, see Exercise 35, apply also to a voltmeter.)

1. A Daniell cell.
2. Two Daniell cells in series, connected copper to zinc.

3. Two Daniell cells in series, connected copper to copper.

4. Two Daniell cells in parallel.

Are the electromotive forces of the individual Daniell cells equal? (Compare 1, 2, and 3.) How does the electromotive force of two Daniell cells in parallel compare with that of a single cell? With that of two cells in series? (Compare 1, 2, and 4.)

5. A Leclanché cell. (Zinc and carbon plates in a solution of sal ammoniac—ammonium chloride.)

6. A Leclanché and a Daniell cell in series, connected carbon to zinc and copper to zinc.

7. The same cells in series, connected carbon to copper and zinc to zinc.

Is the electromotive force of a battery cell altered in any way when it is connected to another cell of different construction? (Compare 1, 5, 6, and 7.)

8. A Grenet cell. (Zinc and carbon in a solution of potassium bichromate and sulphuric acid.)

Remember to lift the zinc plate out of the bichromate solution as soon as you have completed your observations, for if left in, it will soon disappear under action of the acid.

9. A storage cell, using the terminals on the table.

10. A Bunsen cell. (Zinc in a sulphuric acid solution and carbon in a bichromate solution. In the original Bunsen cell the carbon was in concentrated nitric acid.)

III. Measure the electromotive force of a Daniell cell, and of a Leclanché cell, after being short-circuited for fifteen or twenty minutes. Was the electromotive force of the Daniell cell the same as that found in II? Was that of the Leclanché the same? If not, why? Which cell do you conclude is unsuitable for use where a constant current is required, as in telegraphing? Give a reason, if you can, why the other cell would be unsuitable for use where the circuit would only be closed for a moment at a time and at long intervals, as on a bell circuit.

IV. Measure the electromotive force of a cell composed of copper and zinc plates in dilute sulphuric acid; of the same plates in a bichromate solution; of carbon and zinc plates in dilute sulphuric acid; of the same plates in a bichromate solution. Do you find the electromotive force of a cell to depend on the material composing the two plates alone, on the electrolyte alone, or on both? Wash the plates thoroughly and sponge up carefully any acid that may have been dropped on the table.

## 37. OHM'S LAW.

I (*a*). Connect a single Daniell cell in series with a rheostat and an ammeter. Take out enough plugs from the rheostat to introduce a resistance of 5 ohms* into the circuit. Read the ammeter carefully, reversing as usual. (Do not be surprised if the current is small.)

(*b*.) Introduce another Daniell cell into the circuit in series with the first cell. Read the ammeter again.

How does the electromotive force in (*b*) compare with that in (*a*)? How does the current through the ammeter? What relation do you find to exist between the electromotive force and the current when the resistance is constant?

II (*a*). With the connections as in I (*b*) take out enough plugs from the rheostat to increase the introduced resistance to 7 ohms. Read the ammeter.

(*b*.) Repeat II (*a*) with all the rheostat plugs out. (Resistance = 10 ohms.)

How do the currents through the ammeter in I (*b*), II (*a*), and II (*b*) compare? How do the resistances of the circuits compare, neglecting the comparatively small resistance of the

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* The ohm is equal to the resistance at 0° C. of a column of mercury 106.3 cm. long and 1 sq. mm. in cross section.

battery cells? What relation do you find to exist between the resistance and the current when the electromotive force is constant?

What, from the results of I and II, is the relation between the current in a circuit (or part of a circuit), the electromotive force acting through the circuit (or between its terminals, if it is not a complete circuit), and the resistance of the circuit (or part of a circuit)? This relation, when written correctly in the form of an equation, is called *Ohm's Law.*

III. Connect an ammeter and a voltmeter in parallel to the terminals of two Daniell cells connected in series, introducing a rheostat into the ammeter circuit.

Introduce, by means of the rheostat, resistances of 1, 2, 3, 4, 5, 6, 8, and 10 ohms into the ammeter circuit, reading in each case the ammeter and the voltmeter.

Tabulate your results, placing the resistance (in ohms) in the external circuit in one column, the corresponding current (in amperes) in another column, the electromotive force (in volts) in a third column, and in a fourth column the product of the resistance into the corresponding current. According to Ohm's law (see II), what should be the relation between the quantities in the third and fourth columns? Do you find this relation to hold true in every case?

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IV (*a*). If you have not the results of Exercise 36, measure with a voltmeter the electromotive force of a single Daniell cell; of two Daniell cells in parallel; of two Daniell cells in series.

(*b*.) Connect the single Daniell cell directly to an ammeter and measure the current. Repeat with the two cells in parallel, and in series.

(*c*.) From the results of IV, (*a*) and (*b*), calculate, by means of Ohm's law, the internal resistance of a single Daniell cell; of two Daniell cells in parallel; of two in series.

V. Find, as in IV, the internal resistances of a Bunsen cell and of a "dry battery" cell; also the resistance of one of the storage battery circuits. Why can not the resistance of a Leclanché, or other "single fluid" cell, be found in this way?

## 38. DIVIDED CIRCUITS.

I (*a*). Join two rheostats in parallel and connect them in series with a storage cell and an ammeter. Cut out the resistances in the rheostats, leaving but one ohm in one branch of the circuit, and two ohms in the other. Read the current through the ammeter.

(*b*.) Place the ammeter in the branch circuit of one ohm's resistance, and measure the current in this branch.

(*c*.) Measure in the same way the current in the branch circuit of two ohms' resistance.

(*d*.) Answer the following questions:—

1. How does the current in the main circuit compare with the sum of the currents in the two branch circuits?

2. Does the greater current flow through the circuit of greater or less resistance?

3. The currents in a divided circuit are proportional to an integral power of the resistances of the branches. What do your results indicate this power to be? Is it direct or inverse?

II. Repeat I with a resistance of two ohms in one of the divided circuits and of five ohms in the other, and answer again the questions in I (*d*).

III. Connect the two rheostats with a third so as to form three parallel circuits of one, two, and three ohms' resistance, respectively. Measure with an ammeter, as was done in I and II, the current in the main circuit and in each of the branch circuits. Measure with a voltmeter the electromotive force between the two junctions of the parallel circuits.

Is the relation found in I and II between the currents in the branch circuits and the resistances of the circuits confirmed by the results of III?

IV. Calculate from the readings of the ammeter and voltmeter, by means of Ohm's law, the combined resistance of the three circuits in III when joined in parallel. Do you find the sum of the resistances of the separate branches of a divided circuit to be equal to, greater, or less than the actual resistance of the circuit?

The reciprocal of the resistance of a conductor of electricity is called its *conductivity.* Calculate the conductivity of each of the parallel circuits in III separately, and also the conductivity of the three in parallel. Is the sum of the separate conductivities of the branches of the divided circuit equal to, greater, or less than the actual conductivity of the circuit?

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V. Show algebraically that, if Ohm's law is true, the relations found in I and IV must necessarily follow.

## 39. ARRANGEMENT OF BATTERY CELLS, AND FALL OF POTENTIAL ALONG A CONDUCTOR.

I. Connect three Daniell cells in series with each other (zinc to copper), and in series with an ammeter and a rheostat. Measure the current through the ammeter (1) when there is no resistance in the circuit external to the cells; (2) when a resistance of three ohms is introduced; (3) when five ohms are introduced; (4) when ten ohms are introduced.

II. Repeat I with the three cells connected in parallel (coppers together and zincs together).

Which arrangement of cells gave the greatest current when there was no external resistance in the circuit? Which when

a resistance of ten ohms was introduced? Explain why in each case. In general, how should a number of battery cells be connected in order to obtain as large a current as possible (1) when the resistance in the external circuit is very small; (2) when it is comparatively large?

III. Connect three Daniell cells in series with each other and an external resistance of 10 ohms. Beginning at one end of the rheostat, measure with a voltmeter the electromotive force between two points in the circuit separated by a resistance of one ohm, and repeat this measurement for each resistance in the rheostat. Is the electromotive force between two points of the circuit separated by a resistance of one ohm the same in all parts of the circuit?

IV. With the cells and rheostat (or rheostats) connected as in III, measure with the voltmeter the electromotive forces between one of the terminal plates and points on the circuit separated from this plate by resistance of 1, 2, 3, 5, 8, and 10 ohms respectively. Do you find the increase in electromotive force along the conductor to be proportional to the resistance, or not? What is the relation between the electromotive force and the difference of potential? Is the fall of potential then proportional to the resistance, or not?

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V. Repeat IV, starting from the other terminal plate of the battery.

VI. Apply Ohm's law to the case of battery cells connected in series and in parallel and show which would be the most advantageous arrangement when the external resistance is large; and which when it is comparatively small. Are the conclusions arrived at in II from experimental data consistent with those deduced thus from theoretical considerations?

VII. Show that, if Ohm's law is true, the fall of potential along a conductor must follow the law found in IV.

## 40. COMPARISON OF RESISTANCES.—WHEATSTONE'S BRIDGE.

I. Connect a Leclanche cell to the bridge-wire of a Wheatstone's bridge, and connect a sensitive galvanoscope, by one terminal, to the sliding contact. (As the galvanoscope is simply used to show the presence or absence of an electric current, the motion of its needle is restricted to a few degrees.) Connect also two rheostats in series with each other and in parallel with the bridge-wire, and join the free terminal of the galvanoscope to the junction of the two rheostats. A circuit of six branches is thus formed, with the galvanoscope in one branch, the battery cell in another, the rheostats in two branches, and two branches formed by portions of the bridge-wire.

With a resistance of five ohms in each rheostat set the sliding contact so that there is no current through the galvanoscope.

Measure the lengths of the two portions into which the bridge-wire is divided. What is the ratio of these two lengths? How does this ratio compare with the ratio between the two resistances in the rheostats?

II. Repeat I, with resistances of 5 and 10 ohms, respectively, in the rheostats; with resistances of 7 and 10 ohms. What proportion do you find can always be formed between the resistances in the rheostat branches and the two lengths into which the bridge-wire is divided when there is no current through the galvanoscope?

III. What must be the difference of potential between the two points where the galvanoscope is connected when there is no current indicated? Show from the results of Exercise 39, IV, that when this is the case, the proportion found in II must hold true.

IV. Replace one of the rheostats by 100 cm. of No. 25 German silver wire. Adjust the sliding contact so that there is no current through the galvanoscope, and measure the lengths into which the bridge-wire is divided. Using the rheostat resistance as a standard, calculate, by means of the proportion found in II, the resistance of 100 cm. of No. 25 German silver wire.

V. Repeat IV with various coils of wire on the table, instead of the German silver wire, and find the respective resistances of these coils.

## 41. EFFECT OF AN ELECTRIC CURRENT. HEATING.

I. Make a simple calorimeter by placing a small beaker into another a size larger, with a layer of *dry* cotton between. Weigh out about 50 gms. of water a few degrees below the temperature of the room, and place it in the inner beaker. Connect a coil of No. 25 insulated German silver wire in series with an ammeter and the storage battery terminals. Place this coil in the calorimeter, cover it with a perforated cork, and take simultaneous readings of the temperature of the water and the current through the ammeter, every two minutes for about fifteen minutes. (The water in the calorimeter should be stirred whenever its temperature is taken.) What is the effect of the current on the temperature of the coil and of the water in contact with it?

II. Introduce a rheostat into the circuit so as to reduce the current to about three-fourths of its value in I. Repeat the measurements of I.

III. Alter the rheostat resistance so as to reduce the current to about one-half of its value in I, and again repeat the measurements of I.

IV. Reduce the current to about one-fourth of its value in I, and repeat the same measurements.

The heating of a conductor by an electric current is proportional to an integral power of the current. What is this power as indicated by the results of I–IV?

V. Connect another German silver coil of the same length in series with the one used in I–IV. Repeat the measurements of I with one of the coils in the calorimeter; with both in the calorimeter. How do you find the heating effect to vary with the length of a conductor? With the resistance? (See the relation between the length and the resistance found in Exercise 35, I.)

VI. What becomes of the energy expended in maintaining an electric current through a conductor?

The energy expended per second in maintaining an electric current through a conductor is equal, when the proper units are used, to the product of a certain power (see IV) of the current into a certain power (see V) of the resistance of the conductor. If the current is measured in amperes and the resistance in ohms, this product will give the energy expended per second in terms of a unit called the "watt." Calculate in watts the energy per second (*i. e.*, the power) expended in maintaining the current through the German silver coil in I. (Use the average value of the current during the period of observation and the resistance of the coil as marked on it.)

Calculate the heat imparted to the coil per second on the assumption that it is all given up to the water and that the thermal capacity of the calorimeter can be neglected. Express the result in units of energy (or work) per second. [1 calorie per second = 41,900,000 ergs (dyne-cm.) per second.]

Having found the power (energy per second) expended in maintaining the current, and the heat imparted to the coil in a second, calculate the value of a watt in ergs per second.

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VII. Find an expression for the power necessary to main-

tain an electric current in terms of the electromotive force and the intensity of the current, by substituting for the resistance its value (as given by Ohm's law) in terms of the electromotive force and the intensity of the current.

VIII. PROBLEM.—The output of a dynamo on an arc-light circuit is 10,000 watts and the current in the circuit is 8 amperes. What is the resistance of the circuit? What is the electromotive force developed by the dynamo?

## 42. EFFECT OF AN ELECTRIC CURRENT. ELECTROLYSIS.

I. Wash and dry the six plates of three simple copper voltameters and the copper plates of two Daniell cells. Weigh these plates carefully to a decigramme, recording the numbers stamped on the plates for purposes of identification. Place the copper plates in the copper sulphate solution of the voltameters, two plates in each voltameter, separated so that the current will be obliged to flow through the solution between them. Connect the voltameters so that the whole current will pass through one, and one-half the current through each of the other two. Draw a good-sized diagram to show the arrangement of the plates in the voltameters. Replace the copper plates in the Daniell cells and connect the cells in series with each other, and with the voltameters and an ammeter. Indicate on your diagram the direction of the current from the copper plate of the battery through the voltameters and back to the zinc plate. Let the current flow through the circuit for an hour without interruption, reading the ammeter and recording the value of the current every two minutes.

At the expiration of the hour, take the six voltameter and two battery plates, wash, dry, and reweigh them. Record on your diagram the loss or gain in weight of each plate.

II. Answer the following questions:—

1. Did the copper plates of the Daniell cells gain or lose in mass? Did the two gain or lose equally or unequally?

2. In the voltameters, which plates gained in mass and which lost, those by which the current entered, or those by which the current left the liquid? Was the copper carried with or against the current?

3. In each voltameter how did the gain in mass of one plate compare with the loss in mass of the other plate?

4. How did the gain or loss in mass of the copper plates of the Daniell cells compare with that of the plates in the voltameter through which the whole current passed?

5. How did the gain and loss in mass of the plates in each of the voltameters through which only part of the current passed compare with that in the voltameter through which the whole current passed?

6. How did the mass of copper deposited vary with the intensity of the current, assuming that the rate of deposition is proportional to an integral power of the current? (See question 5.)

III. Find the average value of the current in I, and calculate from your results the mass of copper that would be deposited from a copper sulphate solution by a current of one ampere flowing for one second.

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IV. Repeat I with a voltameter consisting of two zinc plates in a zinc sulphate solution, and find the mass of zinc that would be deposited from such a solution by a current of one ampere flowing for one second.

## 43. ELECTRO-MAGNETIC INDUCTION.

PRELIMINARY.—Connect the terminals of a sensitive galvanometer by a copper wire (labeled "galvanometer shunt"), so

that when connected with a battery cell only part of the current will flow through the galvanometer and its deflection will not be too great. The sensitive galvanometer should not be lifted without lowering the suspended needle, and should not be moved about any more than is necessary. Always make sure that the needle is swinging free of the coil. Connect a battery cell to the galvanometer terminals, and, assuming that the current flows in the external circuit from the copper (or carbon) to the zinc plate, determine the direction in which the current flows through the galvanometer from one terminal to the other when its needle is deflected toward the east or the west.

I (*a*). Remove the shunt and the battery connections from the galvanometer, and connect its terminals to a helical coil of insulated copper wire. Find the position of the north pole of a long steel magnet by bringing it near a compass-needle. Insert the magnet suddenly into the coil, noting the behavior of the galvanometer. Was the needle of the galvanometer deflected when the magnet was introduced into the coil? If so, in what direction? What was the direction of the current, if any, induced in the coil considered with respect to the position of the magnet? (Show by a diagram.) Was the induced current permanent or temporary?

(*b*.) Withdraw the magnet from the coil. Did the withdrawal of the magnet induce any current in the coil? If so, how did the induced current compare as regards direction and magnitude with that induced when the magnet was inserted into the coil?

(*c*.) Repeat (*a*), with the poles of the magnet reversed. What effect, if any, did the reversal of the poles have upon the direction and magnitude of the induced current?

Was the field due to the magnet (see Exercise 32) in the same or the opposite direction as that due to the induced current?

II. Repeat I with a bar of soft unmagnetized iron. How did the effect, if any, of introducing the soft iron bar into the coil compare with that obtained when the steel magnet was introduced?

III. Place the soft iron bar within the coil and then touch one end with the north pole of the steel magnet. What was the effect of thus magnetizing the soft iron bar while within the coil? If it had been magnetized by a current in the same direction as the induced current (if there was an induced current), would the direction of the magnetization have been the same or opposite to that which caused the induced current?

IV. Remove the iron bar, and introduce the steel magnet quite slowly, noting the behavior of the galvanometer. Was the induced current as great or greater than in I (*a*) when the magnet was introduced suddenly?

V. Withdraw the steel magnet partially. How did the induced current compare with that in I (*b*) when the magnet was withdrawn wholly?

VI (*a*). Take two parallel concentric coils, one of coarse and the other of fine wire, and connect the one with the fine wire to the galvanometer and the other to the storage battery. Note the effect of making and breaking the circuit in the primary coil (the coil connected to the storage battery) upon the secondary (the coil connected to the galvanometer). With a compass-needle determine the direction of the storage battery current, using the relations found in Exercise 32. If a current was induced in the secondary coil when the circuit was made, was its direction the same as that of the current in the primary, or not? Was it the same when the circuit was broken?

(*b*.) Reverse the direction of the current in the primary and repeat VI (*a*).

(*c*.) Diminish the current in the primary by introducing a resistance into the circuit, and repeat VI (*a*). What effect

did the magnitude of the current in the primary have upon the induced current in the secondary coil?

(*d.*) Repeat VI (*a*) with a bar of soft iron within the coils. What effect did the presence of the iron have upon the induced currents?

VII. Answer the following questions:—

1. What in general was the effect of changing the magnetic field in the immediate neighborhood of an electric conductor forming part of a closed circuit? (See I, III, IV, etc.)

2. Was the effect in every case (see I, III, IV, etc.) such as to diminish, or increase the change in the magnetic field?

3. Did the magnitude of the effect depend in any way on the rate of change in the magnetic field? [Compare I (*a*) and IV.]

4. Did it depend in any way on the magnitude of the change in the magnetic field? [Compare I (*b*) with V, or VI (*a*) with VI (*c*).]

## 44. EARTH-INDUCTOR.

I (*a*). Set up a sensitive galvanometer and connect it with an earth-inductor, placing them as far apart as the table will allow. Place the earth-inductor so that the two stationary upright supports are in an east and west line and set the circle so that its axis of rotation is horizontal.

Turn the circle slowly into a horizontal position, let the galvanometer-needle come to rest, and then turn the circle suddenly through 180°, noting the effect on the galvanometer. Explain the cause of the current produced.

(*b.*) Turn the circle in the same direction through another 180° and compare the induced current with that in I (*a*). Was its direction the same? What would its direction have been if there had been no commutator?

(*c*.) Rotate the coil continuously and uniformly, recording the number of turns per minute and the deflection of the galvanometer.

II. Set the coil so that its axis of rotation is approximately in the direction of the earth's magnetic field. (At an angle of about 62° with the horizontal.) Rotate it continuously as was done in I (*c*), recording again the number of turns per minute and the deflection of the galvanometer, if any. How does the current induced compare with that in I (*c*)? Explain the difference, if there is any.

III. Set the coil as in I and rotate it continuously at a rate either one-half, or twice as great as in I (*c*). What effect do you find a change in the rate of rotation to have upon the value of the induced current?

IV. Repeat I (*c*) with the axis of rotation vertical, rotating the coil as nearly as possible at the same rate. To what component of the earth's magnetic field is the induced current proportional in this case? To what component was it proportional in I (*c*)? How might the angle of dip be calculated from the observations made in this section and in I (*c*)? Using a table of natural tangents, calculate thus the angle of dip at Berkeley.

V. By varying the angle of inclination of the coil find a position for which there will be no current induced when the coil is rotated. Read the angle of inclination, if the earth-inductor has a graduated circle. What is the relation between this angle and the angle of dip? How does the value of the angle of dip found in this way compare with that found in IV?

VI. Turn the base of the earth-inductor through 90° and rotate the coil continuously about a vertical axis as in IV at the same rate. How do you find the induced current to compare with that in IV? Explain the difference, if there is any.

VII. Answer the following questions and give reasons for your answers:—

1. Would there have been any current induced if the coil had been moved parallel to itself?

2. Would there have been any current induced if the coil had been moved parallel to itself with a strong magnet in its neighborhood?

3. What would be the effect on the induced current if a soft iron core were placed within the coil of the earth-inductor?